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[*Continued on page (III) of Cover*

RECENT INVESTIGATIONS ON TELEPHONE INTERFERENCE.

By W. G. RADLEY, B.Sc.(Eng.), and S. WHITEHEAD, M.A., Ph.D., Associate Members.

[REPORT (REF. M/T21) OF THE BRITISH ELECTRICAL AND ALLIED INDUSTRIES RESEARCH ASSOCIATION.]

(*Paper first received* 2*nd November*, 1932, *and in final form* 7*th February*, 1934; *read before* THE INSTITUTION 23*rd November*, *before the* NORTH-WESTERN CENTRE 21*st November*, *and before the* SOUTH MIDLAND CENTRE 4*th December*, 1933.)

SUMMARY.

In a previous paper* by one of the authors, the state of knowledge then existing upon the subject of telephone interference was described. The present paper deals with the results of investigations in Great Britain and elsewhere since completed, and particularly with the series of investigations in which the authors have been concerned. These have been carried out during the past few years under the ægis of the E.R.A., in co-operation with communication and power interests.

Consideration of the subject may be divided roughly under two heads: *disturbance* from harmonics during normal operation of the power system, and *danger* due to excessive induction at the fundamental frequency under transitory fault conditions. The former gives rise to noise and, with regard to its disturbing effect, may be calculated or measured in terms of an e.m.f. at 800 cycles per sec. In the same way the total harmonic output of electrical plant may be expressed by its telephone interference factor. For modern installations this quantity can usually be kept below 1 per cent. Although mercury-arc rectifiers (fully discussed in connection with experiments on traction systems) exceed this value, the telephone interference factor can be reduced to less than 1 per cent by appropriate smoothing equipment.

Both disturbance and danger are generally due to induction from earth currents, a problem which is treated in detail. The magnitude of the currents is investigated for various cases, and it is shown that the induction can be calculated if the earth resistivity is known. Alternative methods of measuring this are available. The screening effect of conductors in parallel (such as telephone-cable and power-cable sheaths, earth wires, and rails) must be taken into account, and formulæ and experimental measurements are given for these. Brief mention is made of cases of induction at close separation.

Although further study of certain aspects is still needed, it is concluded that theory and experience are available for the approximate calculation and predetermination of the amount of interference likely to occur in any given case. Possible methods of prevention are indicated in various sections of the paper.

CONTENTS.

(1) NATURE OF INTERFERENCE.

(*a*) *Interference in Normal Operation: Noise and its Measurement.*

(i) *Origin and Effect of Disturbance.*—Transmission of speech over telephone circuits is impaired by noise added by induction from the harmonics of electric power systems. Disturbance results generally from the normal operation of the power system, and in the case of transmission lines is frequently due to harmonics which are multiples of the third and therefore additive in their inductive effects. Another common cause is the ripple

* See Bibliography, (2).

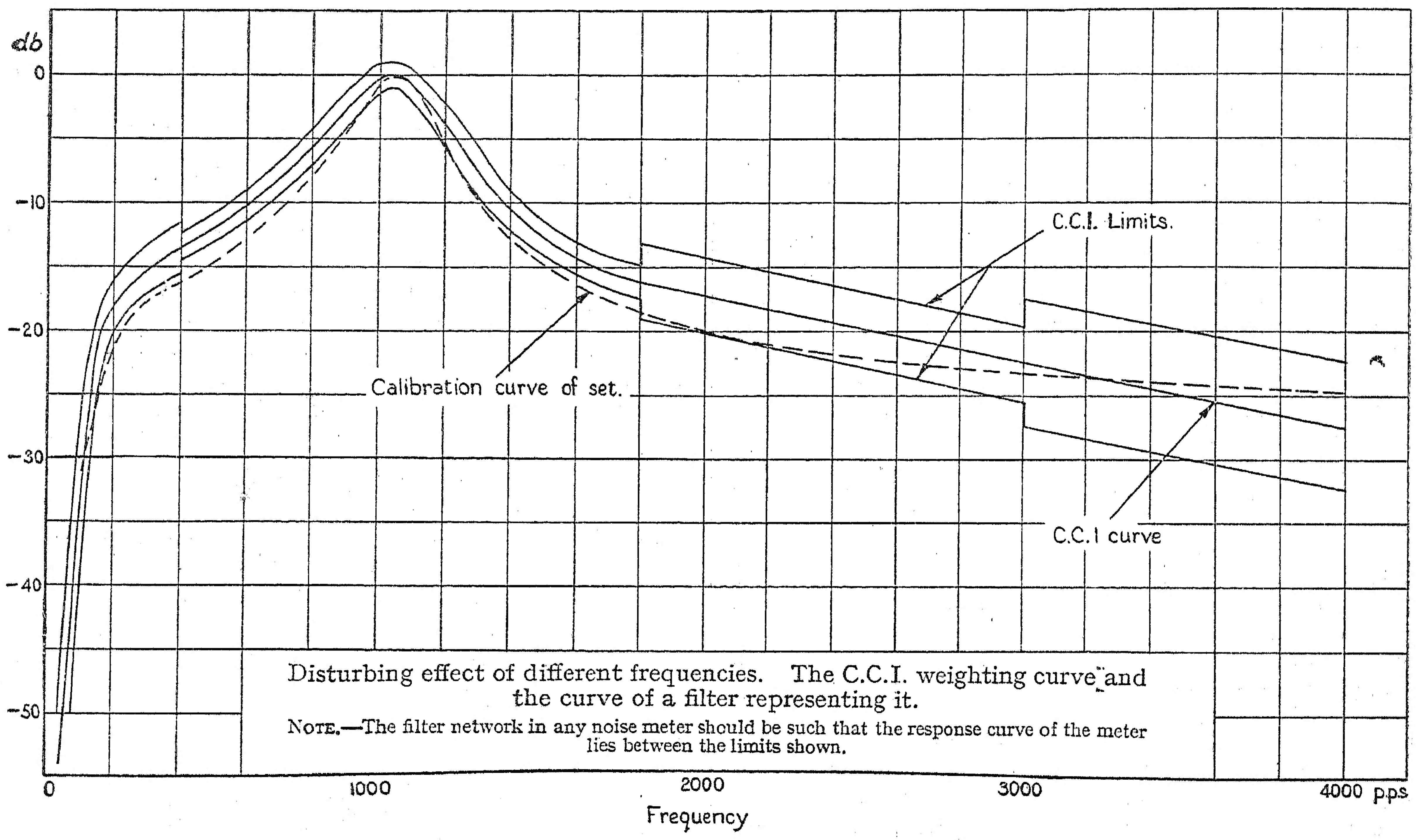
currents in a d.c. contact line feeding an electrified railway.

In the experimental work which is to be described, disturbance has always been investigated from the standpoint of its effect on telephone circuits. These circuits form by far the greater part of all communication circuits. In addition, many telegraph circuits are now being worked over a loaded and repeatered pair by means of modulated voice-frequency current. From the point of view of interference, these require separate consideration. Permanent interference with earthed telegraph circuits may result from induction at the fundamental frequency.

In 1919 Osborne showed that the loss of quality of the transmission resulting from the addition of a voltage at a frequency within the audio range to a telephone circuit was connected in a fairly definite way with its frequency. In the laboratory it is usual to measure the loss in quality by means of what is known as an articulation test, although other methods, such as the repetition rate method, which approximates even more closely to the practical conditions under which telephone conversations are carried on, are being experimented with by the Post Office. More recently the Comité Consultatif International des Communications Téléphoniques à Grande Distance (C.C.I.) has published a curve, shown in Fig. 1*, giving the relative interfering effects of single-frequency voltages over the frequency range where power-circuit interference is experienced. This curve has been based on a large number of tests carried out at different times in America and with different observers. Allowance has been made for the recent developments in the design of telephone receivers. Table 1 gives the relative weighting of voltages across the receiver for frequencies of importance in connection with 50-cycle circuits.

(ii) *Measurement of Noise: Telephone Interference Factor.*—Based on the weighting curve shown in Fig. 1, a noise meter can be constructed which will indicate objectively the voltage at a fixed reference frequency equivalent to any single-frequency disturbance as regards degradation of articulation. In practice 800 cycles per sec. is taken as the reference frequency and the noise voltage on the circuit is defined as the equivalent 800-cycle voltage induced in it.* Noise meters of this type have been constructed by the British Post Office† and also by other telephone administrations, and have been used in some of the investigations to be described later. The actual weighting curve of a recent Post Office meter, obtained by means of an electrical attenuating network, has been inserted in Fig. 1.

When used to measure a noise consisting of a mixture of two or more frequencies, the meter will give a reading corresponding to the square root of the sum of the squares of the individual effects. Experiments are being carried out by the Commission Mixte Internationale pour les Expériences relatives à la Protection des



Disturbing effect of different frequencies. The C.C.I. weighting curve and the curve of a filter representing it.

NOTE.—The filter network in any noise meter should be such that the response curve of the meter lies between the limits shown.

FIG. 1.

* Fig. 1 gives the weighting in a scale of decibels, which is a logarithmic power ratio generally used in telephone transmission. The number of decibels between two powers P_1 and P_2 is $10 \log_{10} (P_1/P_2)$. The corresponding voltage ratio is given by:—

$$\text{Number of decibels} = 20 \log_{10} (V_1/V_2)$$

* When subjective tests were made by means of comparison with an 800-cycle tone, the noise voltage was carefully defined by the C.C.I. as the e.m.f. at 800 cycles per sec. which, working through a special receiver of impedance at 800 cycles per sec. equal to that of the line, in series with an impedance equal to the line impedance at 800 cycles per sec. assumed to be 600 ohms, produces the same effect upon the ear as is produced by the same receiver when this is connected at the end of the line under observation.

† See Bibliography, (23).

Lignes de Télécommunication et des Canalisations Souterraines (C.M.I.) to determine whether the effects of a complex noise can be represented by such an addition law.

In conjunction with circuit models which enable the line to be terminated with an exchange circuit, local line, and subscriber's circuit, a noise meter may be connected as a voltmeter across the subscriber's receiver. Although this has the advantage that the noise is actually measured where it is heard, the method is not suitable for use when international lines are concerned, as the attenuation/frequency characteristics of the terminations appropriate in the different countries are not equal.

The requirements of telephone circuits used for broadcasting are much more stringent. Noise meters constructed for measurements on these circuits should have a weighting curve corresponding to the threshold-of-audibility curve of the ear throughout the frequency range, but the matter requires investigation.

The foregoing considerations give rise to the definition of the *"equivalent disturbing voltage"* for the power line. This is, by definition, the e.m.f. at 800 cycles per sec. which, when applied to a power line, produces in a neighbouring telephone line the same disturbance as the operating voltage of the power line with all its harmonics, on the assumption that the characteristic coupling coefficient between the lines (capacitance or coefficient of mutual induction) is independent of the frequency. The equivalent disturbing current is defined in a similar manner.

TABLE 1.

Frequency ..	150	450	750	1 050	1 350
Relative effect .. (C.C.I. weighting)	0·17	0·45	0·84	1·93	0·67
Frequency ..	300	600	800	900	1 200
Relative effect .. (C.C.I. weighting)	0·32	0·56	1	1·41	1·26

Noise meters of the type described can be utilized to measure equivalent disturbing voltage and current in a power line. The form of coupling will depend on the type of system and the kind of interference anticipated. Sometimes the components must be magnified in proportion to their order, and sometimes not. In the first case an inductive coupling is used and in the second a direct coupling, as will be mentioned in Section (2).

The equivalent disturbing voltage expressed as a percentage of the fundamental or total voltage is known as the *"telephone interference factor"* or T.I.F.* The term may be applied similarly to a current.

* The T.I.F.'s given in this paper cannot be directly related to those measured by the original (Osborne) T.I.F. meter, as, in addition to the method of expression being different, they are based on two different weighting curves. Assuming a disturbing voltage at 800 cycles per sec., the T.I.F. as defined in the present paper would be about 1/40 of that read by the original meter.

(*b*) *Interference in Transitory States: Danger.*

(i) *General.*—Apart from the risk of electric induction at crossings, or where power and communication lines come into close proximity, the risk of danger is that of magnetic induction from earth-fault currents. The factor which enables the induced voltage to be calculated is the coefficient of mutual induction between the two circuits. Under these conditions the resistivity of the earth has a very important effect, as it alters the distribution of the fault current in the earth, on which the coefficient depends. Considerable attention has therefore been given, first, to establishing by means of field measurements the theory upon which the calculation of the coefficient of mutual induction is based, and secondly, to the collection of sufficient experimental data to enable a value to be assigned to the resistivity in a case where the geological characteristics are roughly known.

The experimental measurements described in Section (3) have been made under steady-state conditions of the earth current. The question whether measurements made in this way could be safely utilized for calculating the induced voltage in the communication line during the first few microseconds of an earth fault has recently been investigated.* It is concluded that they are not likely to be materially exceeded.

Induction in the telephone circuit takes the form of a longitudinal voltage between the two ends of the circuit. At one or both of the ends a dangerously high potential is set up between the apparatus connected to the circuit and earth. Apart from possible damage to apparatus, the danger is that of electric shock, perhaps fatal, to staff working on the telephone line at the time, and acoustic shock to telephone operators and the public.

The C.C.I. Directives† state that if the induced voltage on the telephone line exceeds 300 volts the line must be regarded as exposed to danger. In this country, endeavours are made to reduce exposures or to limit the earth-fault current accordingly.

(ii) *Protective Devices.*—On the Continent of Europe, where high-tension systems with isolated neutrals are extensively used, the problem of protection from acoustic shock has become of relatively greater magnitude than in this country. Use has been made of devices of various kinds for the protection of telephone operators. Two types of coherer protectors (Steidle's and the *"frittersicherung"*), the A.E.G. transformer-coupled arrestors, and the Boyé interrupter, may be quoted. Devices based on the use of thermionic valves and of metal rectifiers have also been tried. Such devices are not dealt with in this paper as they have not so far been fitted to any line in this country, although a close watch is being kept on Continental development. At present it seems that protection from acoustic shock cannot, on economic grounds, be given by means of the above devices to the public generally.

(2) Noise Factors of Power Installations.

(*a*) *General.*

The assemblage of harmonics in the voltage wave of generating and transforming plant is applied to the

* See Bibliography, (6). † *Ibid.*, (1).

distributing and consuming system, and gives rise to currents of corresponding frequencies. If the system is mainly resistive as regards these currents, they will appear in the induced e.m.f. jointly proportional to the magnitude and frequency of the corresponding harmonic voltages, as for direct electrostatic induction. If the system is mainly reactive to these components, the currents will be reduced in proportion to the frequencies, so that the induced e.m.f. will contain the components in the same proportion as in the power voltage. Although this classification is rather arbitrary in practice, it has been adopted by the C.M.I. The "weighting values" previously discussed must be multiplied by the frequency factor* for the first type and can be used

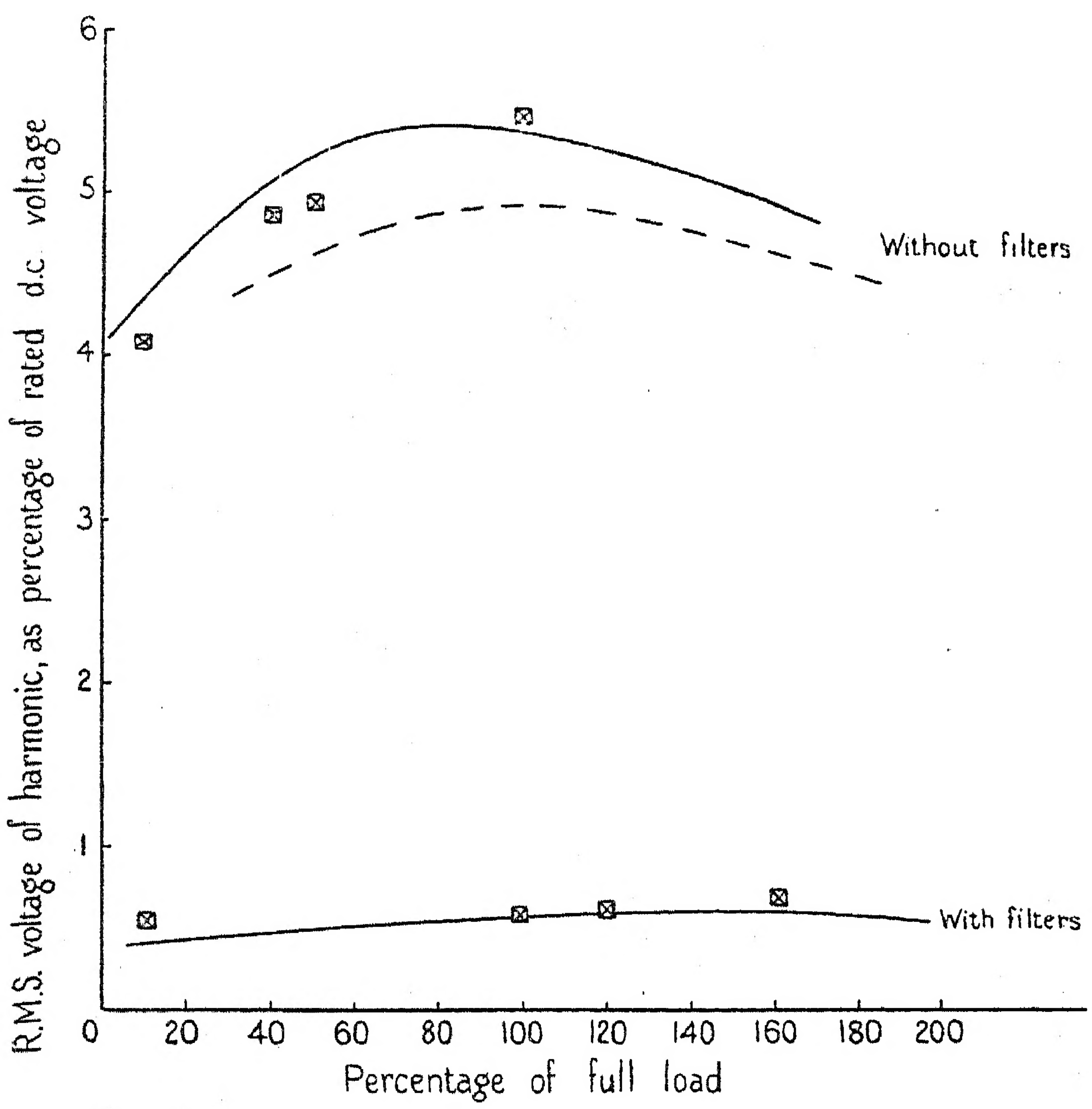


FIG. 2.—Sixth harmonic, 300 cycles per sec.

——— Test loads.
- - - - Service loads: rectifier alone, without filters.
⊠ Service loads: rectifier in parallel with rotary convertor.

NOTE.—With filters, the curve for service loads with rectifier alone coincides with the curve for test loads.

without such a factor for the second type. As the second type is more common to British conditions, in dealing with the relative effects of installations the telephone interference factor will be arrived at by using the normal weighting values.

(*b*) *A.C. Systems.*

Large turbo-alternators have usually a good wave-form, the T.I.F. lying between 0·2 and 0·6 per cent.,† although values up to 1·5 or 2 per cent have been observed. The phase-to-neutral voltage, which contains the residuals, is the more important. Smaller alternators are liable to one or two exaggerated harmonics, so that the usual range of T.I.F. is 0·2 to 1 per cent.* Single-phase generators for a.c. traction are commonly made for $16\frac{2}{3}$ cycles per sec., and consequently the harmonics are of low frequency and the T.I.F. rarely exceeds 0·4 per cent.

With large 3-phase systems the wave-form in the system is only partly due to the generators, owing to the presence of transformers and the transmission constants of the lines. Tests made at Portobello† on the Scottish grid system gave a T.I.F. of 0·3 to 0·7 per cent under various conditions. Measurements on the Continent give a mean range from 0·2 to 0·65 per cent, although higher values have been observed. The important question of the flow of harmonic currents in such systems is considered in a later section.

With single-phase traction circuits the effect of the train load may cause an increase of T.I.F. at a distance from a substation. Values up to 1 per cent, with higher momentary readings, have been observed.

(*c*) *D.C. Systems.*

Modern rotary convertors have usually only small ripples, unless they are fed from a distorted a.c. supply. The provisions of B.S.S. No. 172—1927 would permit a T.I.F. of 2·2 per cent in the worst case, but the average of modern machines is about 0·6 per cent, being less with light loads. A round figure of 0·5 per cent is usually taken for good machines. D.C. generators are not of importance from the interference aspect in British practice. Continental tests on large generators give values from 0·1 to 0·5 per cent, but 1·5 and 2·5 per cent have been observed even with large machines (1 000 kW), which are usually better than small ones. Nevertheless, d.c. generators may usually be designed to be as satisfactory as rotary convertors, but care is necessary.

Mercury-arc rectifiers may be considered in rather more detail since, although the output ripples are calculable, the equipment is a recent and popular development. A series of tests were made on a 1 500-kW 1 500-volt hexaphase rectifier,‡ and Figs. 2 and 3 show the values of the harmonics (multiples of the 6th) under various steady-test loads and the varying loads of service. Fig. 4 shows the variation of T.I.F. of voltage and current with load, compared with the noise observed on a neighbouring P.O. earthed circuit and on search coils placed at distances from the track. Since the induced noises were expressed per ampere of track current, they vary with the T.I.F. of the current. The total noise would have increased with load, as does the T.I.F. of the voltage.

In this case the voltage T.I.F. varied from 1·6 to 3 per cent with load. A large number of tests for the C.M.I. in various countries gave values from 2 to 4·5 per cent, but an average value of 3·5 per cent is more appropriate, assuming a good supply wave-form, since a rectifier is sensitive to the latter. Rectifiers with polarized grids give higher values of T.I.F., according to the evidence so far available.

* If f_0 (usually 800) is the standard frequency, the factor is (f/f_0), where f is the frequency of the component.

† For example, the analysis given by Coe (see Bibliography, 14) of a 30 000-kVA turbo-alternator and 240-kVA motor-alternator lead to T.I.F.'s of 0·33 and 0·84 per cent respectively. Tests by the authors on a number of oil-engine sets (400 to 800 kVA) gave values of about 0·6 per cent (see Bibliography, 20).

* See footnote in column 1.

† See Bibliography, (26).

‡ *Ibid.*, (12) (Tests on Manchester–Altrincham railway).

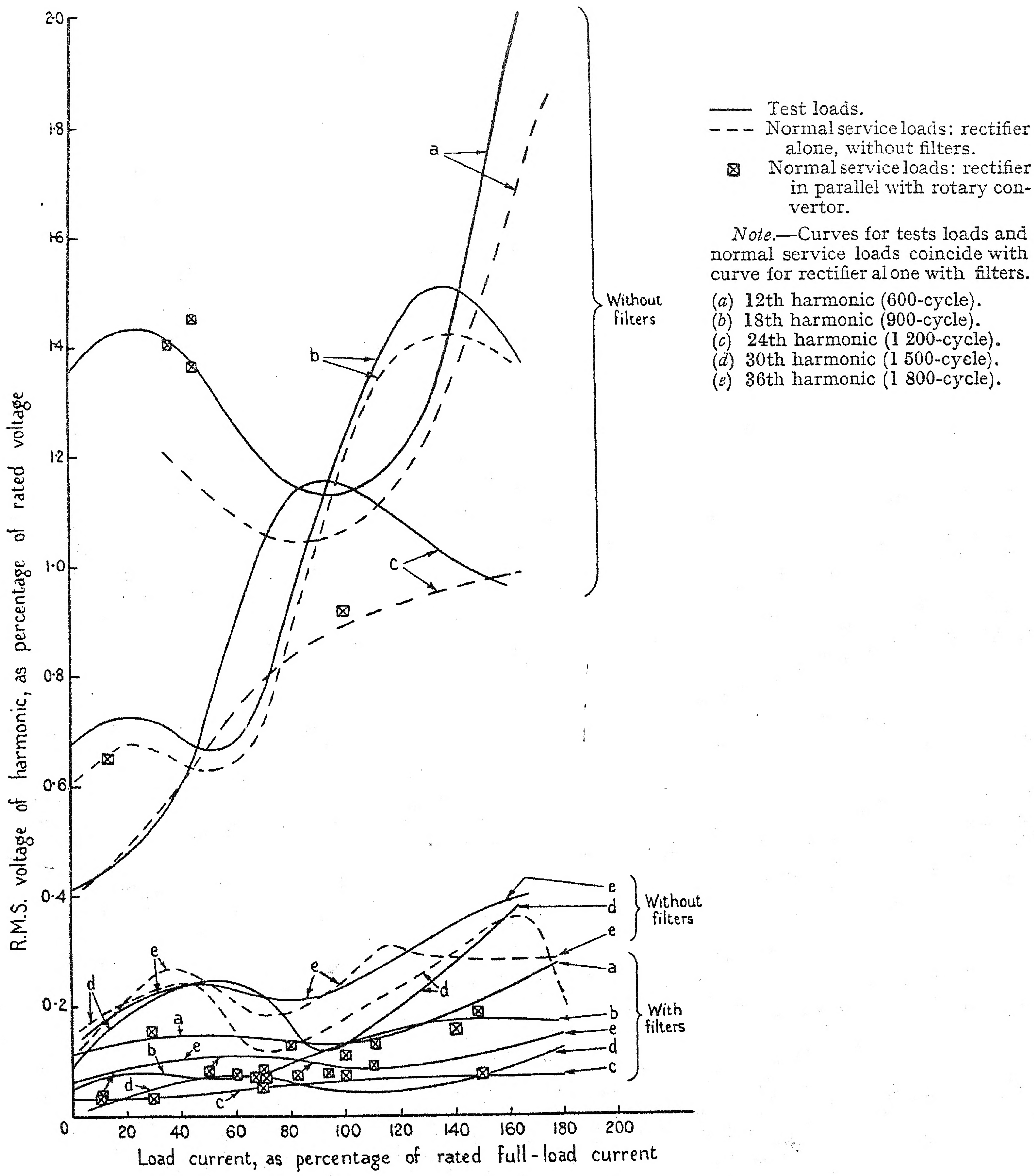


FIG. 3.

The main disturbing harmonics—the 6th, 12th, 18th, and 24th—may be reduced to about one-tenth by the use of four resonant shunts tuned to these frequencies and a reactor in series with the output. Figs. 2 to 4 illustrate this effect on separate harmonics and on overall effects. Fig. 5 shows the reduction of induced noise, which varies according to the distance of the communication circuit from the track owing to the fact that the coefficient of mutual induction decreases more rapidly with distance for the higher frequencies. The usual order of reduction will be taken as about 10 : 1, so that rectifiers with filters may be as satisfactory in general as good rotary convertors. All the shunts are usually necessary.*

(*d*) *Deviation, and Telephone Interference Factor.*

A number of rules are issued by the British Standards

* It is of interest to show the effect of leaving out a filter, as in the following table obtained from tests at Manchester: a given filter mainly affects the frequency to which it is tuned.

Filter omitted for frequency (cycles per sec.) ..	None	300	600	900	1 200	All
Resulting disturbance on P.O. circuit	1	2·6	1·55	3·8	2·3	9·1

Institution as to the amplitude of ripples. The International Electrotechnical Commission has under consideration the determination of "deviation" by measuring (with a filter bridge or other device) the the average modern case we might assume three frequencies, 300, 1 000, and 2 000 cycles per sec., with ratios of $2:1:0 \cdot 2$. In such a case the r.m.s. sum of the harmonics would be $1 \cdot 2$ times the T.I.F., while the

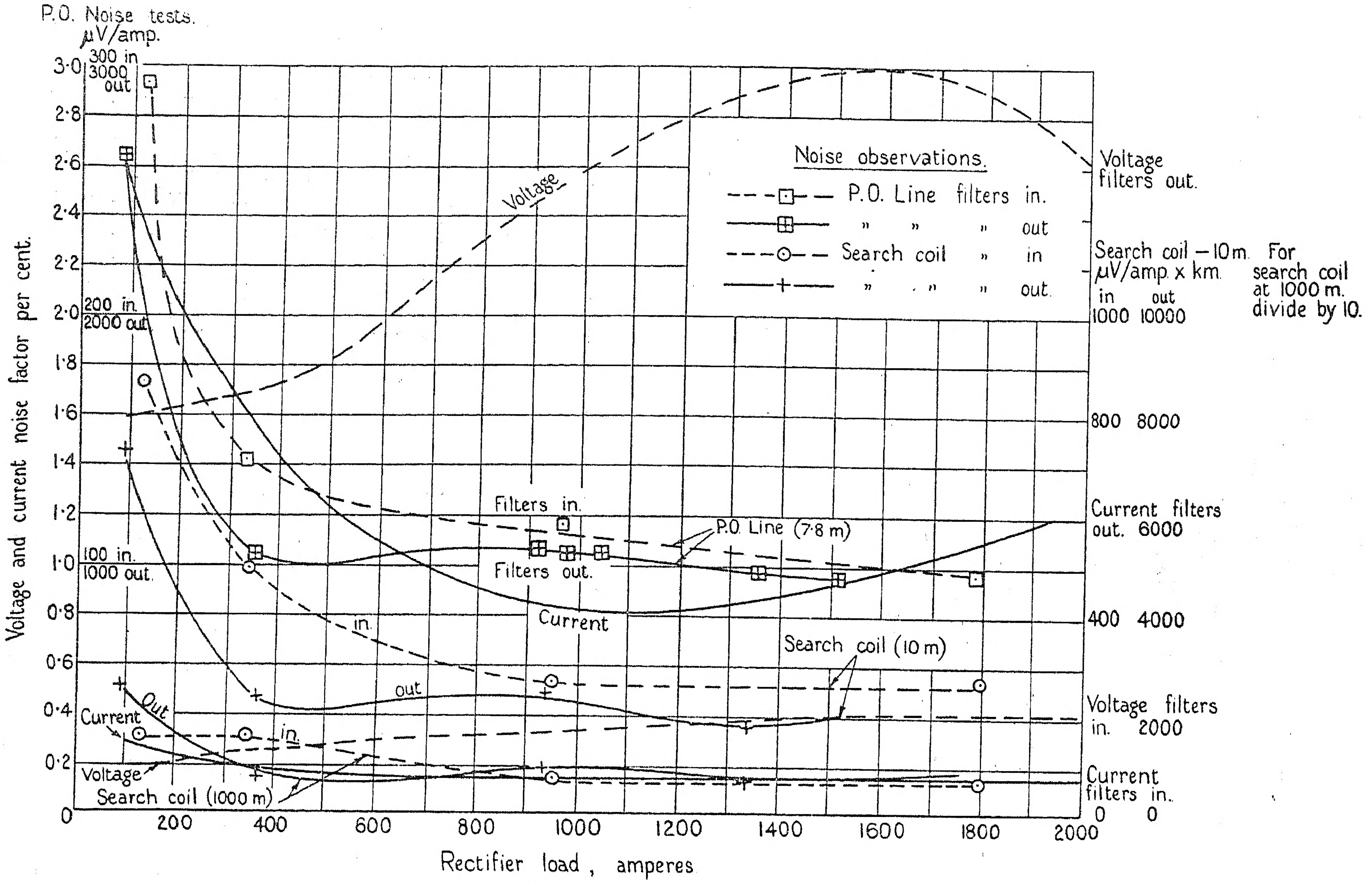


FIG. 4.—Variation of noise factor with load.

r.m.s. sum of the harmonics, the 3rd being excluded, in the line-to-neutral voltage. The C.M.I. and C.C.I. recommend the objective noise-measuring set adapted to read the telephone interference factor (T.I.F.) already described.

A certain correlation sometimes exists between the various methods. For example, a mercury-arc rectifier gives about the same proportions of different harmonics, say, $6:1 \cdot 5:1 \cdot 5:1$ for the 6th, 12th, 18th, and 24th respectively. If one could define a deviation from direct current as the square root of the sum of the squares of the harmonics, then this deviation would be very nearly twice the T.I.F., both being given as percentages of the continuous component. The actual amplitude of the ripple depends on the phase relation of the components, which may not be so constant. For rotary convertors, B.S.S. No. 172 places a limit of $1 \cdot 5$ per cent on the high-frequency tooth and commutator ripple, and 3 per cent on the low-frequency ripple. The former may be of two frequencies, one between 600 and 1 200 and one between 1 200 and 2 400 cycles per sec., while the latter is of 300 cycles per sec. If x is the actual percentage value of the high-frequency ripple and y that of the low-frequency ripple, then a safe figure for the T.I.F. would be $\sqrt{(4x^2 + 0 \cdot 1y^2)}$. If we may assume $y = 2x$, then the T.I.F. will be about $2x$. Actually in

amplitude of the low-frequency ripple would be $1 \cdot 05$ times the T.I.F. and the amplitude of the high-frequency ripple about half that value. Similar relations would

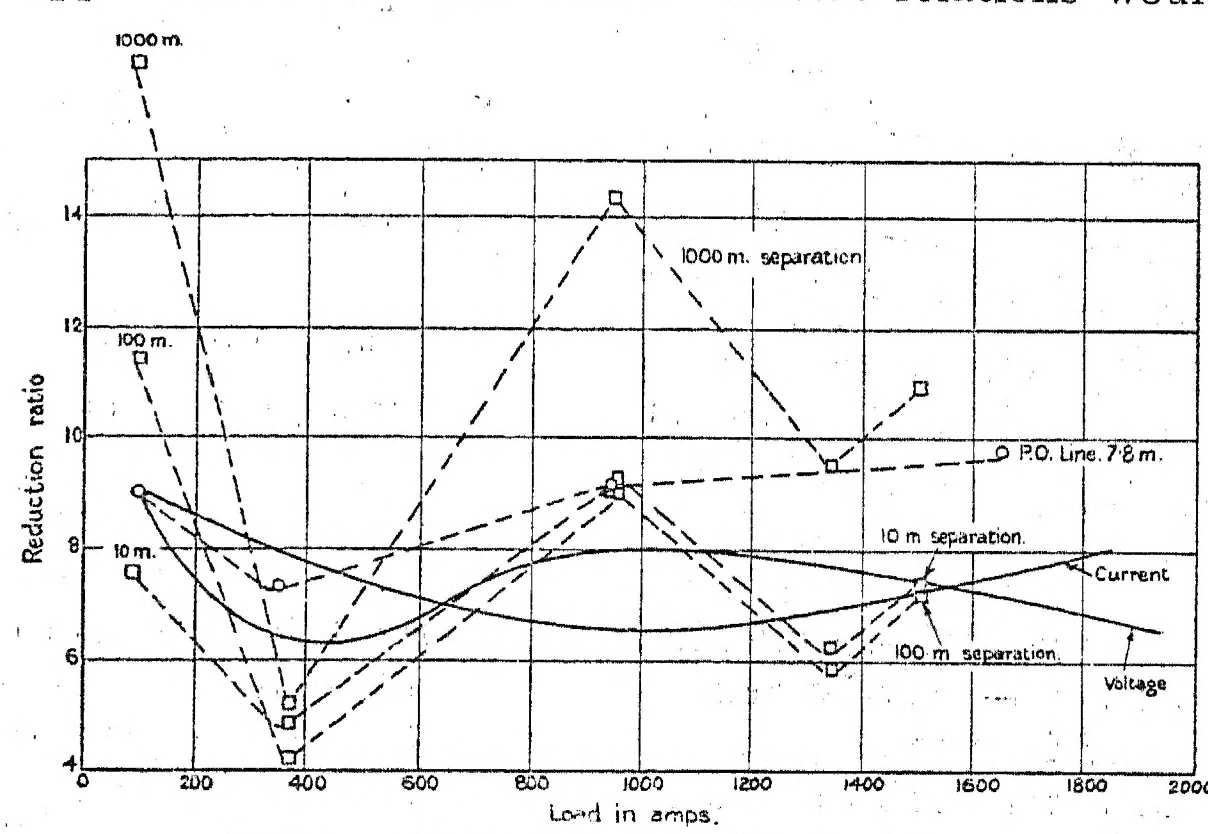


FIG. 5.—Noise reduction due to filters.

○ Measurements on earthed P.O. circuit.
□ Search-coil measurements.

apply to d.c. generators if the same kind of assumptions were made.

Owing to the variation of harmonic distribution, a.c. machines cannot easily be treated in a similar manner,

as is illustrated in Table 2 (taken from cases already cited).

TABLE 2.

Machine	Oil-engine alternators	Oil-engine alternators	240-kVA motor-alternator	30 000-kVA turbo-alternator
	per cent	per cent	per cent	per cent
Sum of harmonics above 3rd..	1·55	1·47	1·23	0·32
T.I.F.	0·63	0·61	0·84	0·33

Correlation is thus ultimately only possible if equipment can be classified into types to which can be assigned an average harmonic distribution. Although, except in certain cases, such a course would be difficult, yet, since the accuracy required is quite low, the matter might profitably be pursued on a statistical basis.

(3) INTERFERENCE FROM EARTH CURRENTS.

(a) Overhead Lines.

(i) *Induction from Earth Currents.*—As mentioned in Section 1 (*b*), the determination of the coupling between two parallel earth-return circuits is a problem of the greatest technical importance.

Theoretical solutions* of the distribution of an alternating current flowing uniformly in a homogeneous earth have been given by Carson† and Pollaczek‡ and have been adopted by the Joint Committee of the National Electric Light Association and the Bell System (America), and by the C.C.I.

The most general form of the expression gives

$$M = \frac{-4j}{\gamma^2} + 4\frac{kei'\gamma - j\,ker'\gamma}{\gamma} \quad . \quad . \quad . \quad (1)$$

where

M is the generalized coefficient of mutual induction between the inducing line and the induced line;
$\gamma = x\sqrt{(4\pi\sigma\omega)}$;
$\omega = 2\pi \times$ frequency of inducing current;
$\sigma =$ conductivity of the earth; and
$x =$ separation of the two circuits.

All the above are measured in absolute C.G.S. units. Equation (1) is true for all separations when both induced and inducing lines are on the surface of the ground, and for all but comparatively close separations when they are suspended on poles.§ In the latter case the height of the lines must be taken into consideration. Appropriate formulæ are given in the C.C.I. Directives and elsewhere.*

The e.m.f., E, induced in a secondary line by a residual earth current I in the primary line, is given by

$$E = -j\omega MlI \quad . \quad . \quad . \quad . \quad . \quad (2)$$

l being the length of the parallel. Although expressed in henrys, M is a *complex* quantity, since the coupling is partly resistive and partly reactive. This practice is followed in Europe and in the present paper, but in America the coupling is always given as a mutual impedance between the circuits. This view is more in accord with physical fact, and it is often easier to introduce appropriate modifications—as for end effects—if the impedance is divided into resistive and reactive components.

Often in practice the earth conductivity varies with depth. A modified formula applying to two layers has been derived by Riordan and Sunde, also in an unpublished E.R.A. report.† The conductivity also varies greatly from place to place, a range of 1 000 to 1 being observable in England. A survey is at present in progress and the results will be published later.

Experiments in Germany at Doberitz, Oldenburg, and Munsingen,‡ with specially-constructed inducing and induced lines gave agreement with theory from $16\frac{2}{3}$ to 2 000 cycles per sec. provided the conductivity was assumed inversely proportional to the square root of the frequency. In actual fact,

$$\sigma = 1\cdot5 \times 10^{-12}/\sqrt{(f)} \text{ C.G.S. units} \quad . \quad . \quad (3)$$

Later, similar tests at Skillingaryd (Sweden) gave a value for σ of $4\cdot4 \times 10^{-15}$ C.G.S. units, which did not vary with frequency. Recently-published tests by Collard§ in England using a long inducing line and short induced lines also gave values of σ independent of frequency, the magnitudes varying according to locality. The variation with frequency encountered in the German tests was probably due to the superposition of a low-conductivity layer of earth on one of higher conductivity.

Early measurements in Great Britain with which the authors were associated were made at Runcorn in 1928 and at Bedford in 1929.‖ In both of these cases the earth current was that flowing from an existing power line, the induced voltage being measured on existing Post Office lines and on lines specially constructed parallel to the power line. These measurements were made at one frequency only (50 cycles per sec.), and showed that over the range of separation concerned the variation of the coupling was of the order predicted by theory. The induced voltages measured at Runcorn and Bedford were consistent with mean earth-resistivities equal to 1 000 and 2 000 ohm-cm respectively.

More extensive measurements were made at Shap¶ in 1931 in co-operation with the C.M.I. Testing-vans used in previous Continental tests were loaned by the German Reichspost. Special lines were constructed (Fig. 6) and measurements were made from $16\frac{2}{3}$ to 2 000 cycles per sec. The inducing line was erected on light poles, but the use of insulated cable lying on the ground

* These solutions form part of the more general scheme of solutions of eddy-current problems discussed elsewhere by one of the present authors (see Bibliography, 15), and are derived from the same analysis.
† See Bibliography, (3). ‡ *Ibid.*, (4).
§ Tables of *ker'* and *kei'* functions are given with the British Association's Report of 1915, pages 36 to 38. Fig. B, page 238, gives curves which enable M to be read off directly when the parameter $x\sqrt{(\sigma f)}$ is known.
If $s =$ separation in metres, and $\rho =$ specific resistance of the earth in ohm-cm; then when $s\sqrt{(f/\rho)}$ exceeds 350 the magnitude of M is given sufficiently closely, for most practical purposes, by $M = 10^6\rho/(2fs^2)$ μH per kilometre.
In this case, that of wide separation, the angle between the inducing current and the induced voltage is approximately 180°. The higher-frequency tests on a line at Shap at 2 000 metres' separation (see page 208) approximated to this.

* *Journal I.E.E.*, 1931, vol. 69, p. 1135.
† See Bibliography, (27) and (29). ‡ *Ibid.*, (5).
§ *Ibid.*, (8). ‖ *Ibid.*, (17). ¶ *Ibid.*, (10)

for the induced lines gave rather variable results at the higher frequencies, owing to capacitance coupling and leakage, but the mean values were consistent. The variation was especially evident in the measurement of the phase angles.

The measured values of the coefficient of mutual

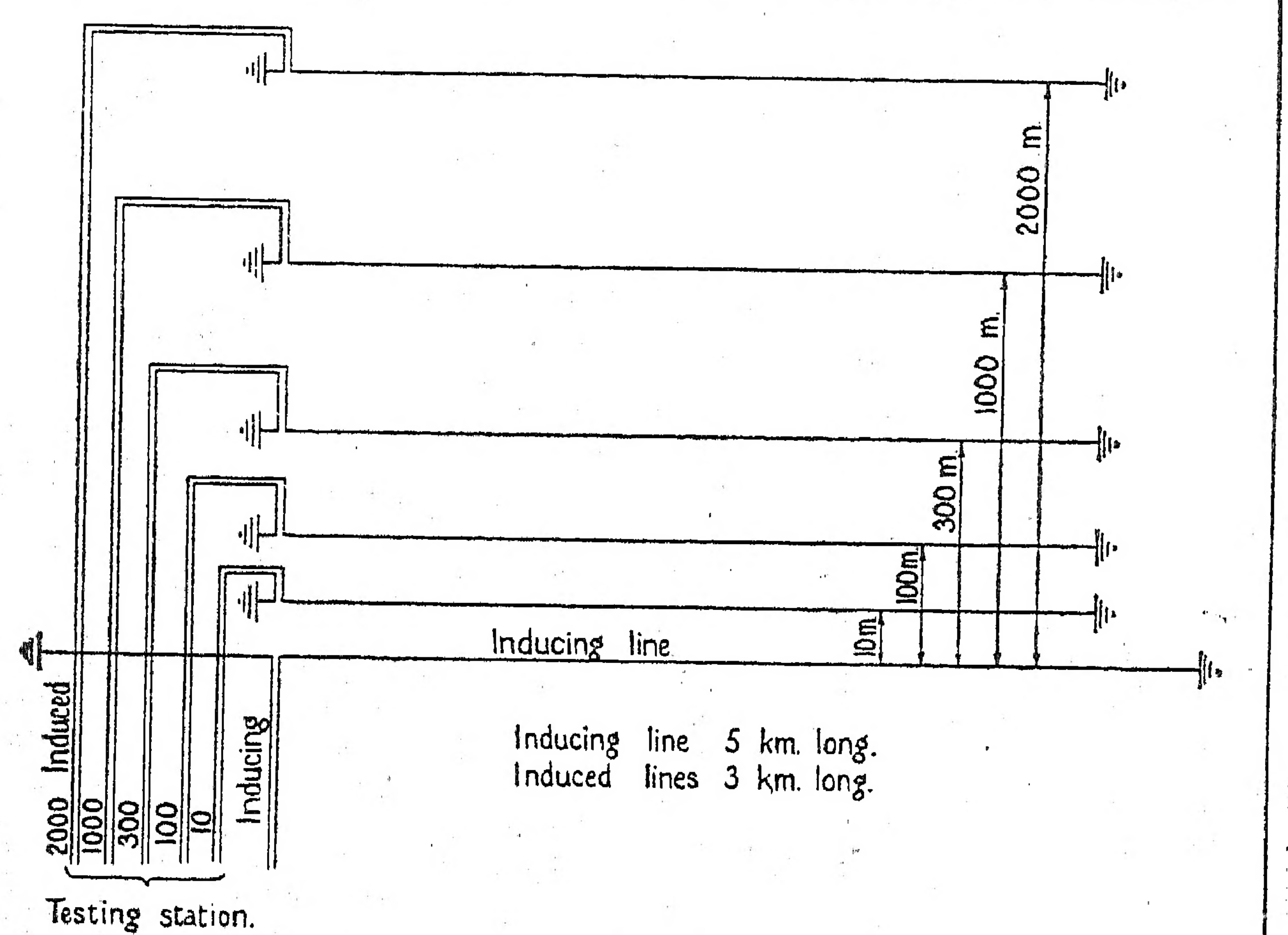


FIG. 6.—Lay-out of test lines at Shap.

induction are given in Fig. 7. They are in agreement with the Carson–Pollaczek theory and an earth conductivity of $4\cdot5\times10^{-15}$ C.G.S. units. Theoretical curves for this conductivity are shown in Fig. 7. For the two closest separations, values of $6\cdot5\times10^{-15}$ and $5\cdot5\times10^{-15}$ C.G.S. units respectively would give better agreement.

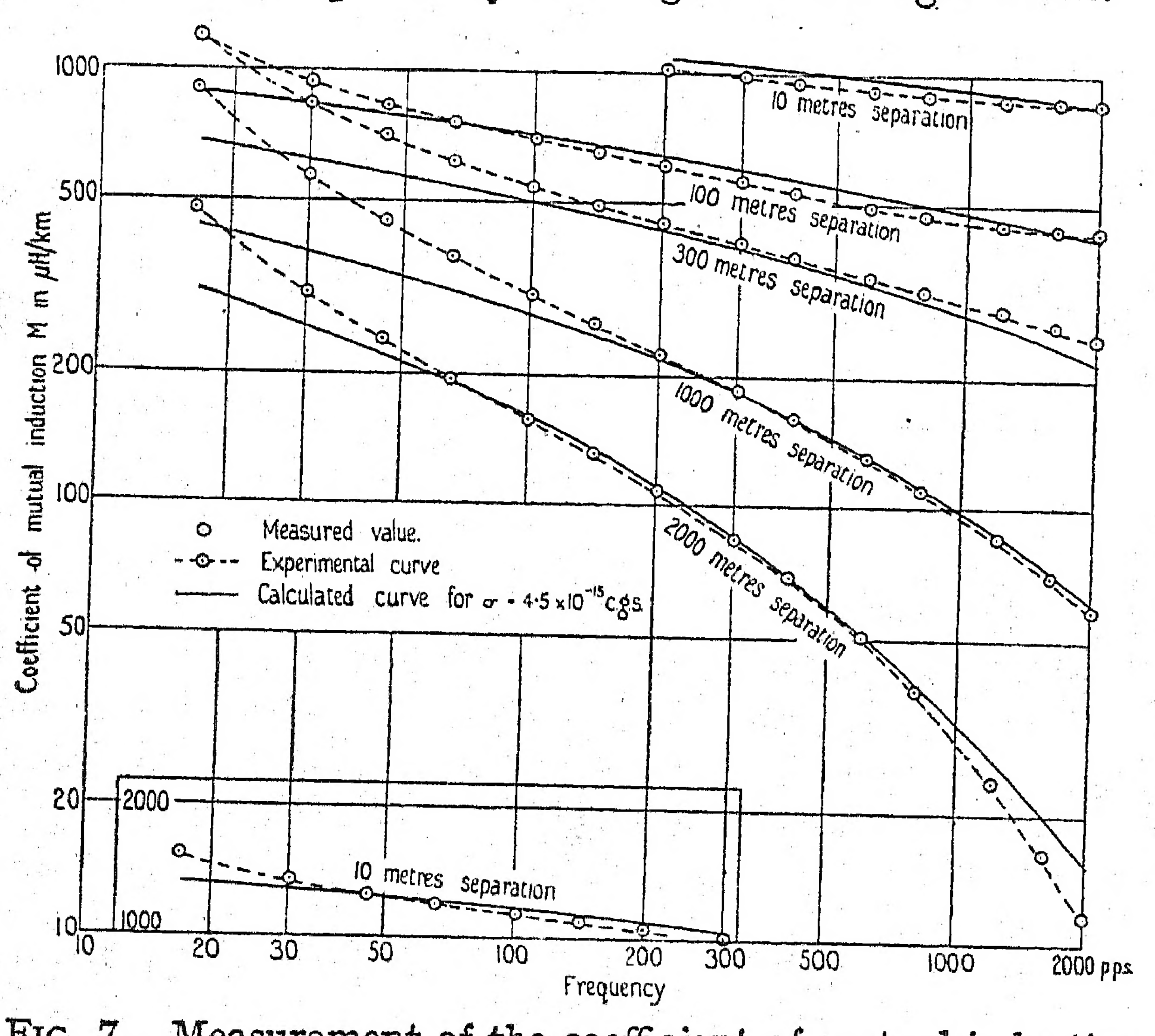


FIG. 7.—Measurement of the coefficient of mutual induction between earth-return circuits at Shap. Variation of *M* with frequency.

The value of $4\cdot5\times10^{-15}$ C.G.S. units deduced from the mutual-induction measurements was in agreement with values of 4×10^{-15} to 5×10^{-15} C.G.S. units found for the lower geological formations from a direct resistivity survey by 4-electrode tests. Values from 5×10^{-15} to 10×10^{-15} C.G.S. units, found from the survey for the surface layers, agree with the higher values found in the mutual-induction tests at close separations.

For all the lines, at frequencies below 100 cycles per sec. there began to be considerable divergence between both the measured coefficients of mutual induction, the measured angles, and the calculated values of these quantities, assuming an infinitely long inducing line. When, however, the measured values of the coefficient of mutual induction were separated into resistive and reactive components, and these were compared with the corresponding theoretical values calculated from equation (1), it was found that the increase was confined to the resistance component.

At $16\frac{2}{3}$ cycles per sec., the lowest frequency at which measurements were made, measured values of the mutual resistance for the 3-km lines were in excess of the calculated values by the amounts shown in column 2 of Table 3.

TABLE 3.

Separation from inducing line (metres)	Mutual resistance, ohms	
	Excess of measured over calculated value at $16\frac{2}{3}$ cycles per sec.	Measured d.c. coupling
10	0·22	0·235
100	0·24	0·250
300	0·28	0·310
1000	$0\cdot21_5$	0·255
2000	0·10	0·135

The coupling between the primary-line earth plates and those terminating each of the five secondary lines was measured with direct current. The results are given in column 3 of Table 3, and correspond with the observed excesses almost within the limits of experimental error. In reality, therefore, there may be said to be excellent agreement with theory throughout.

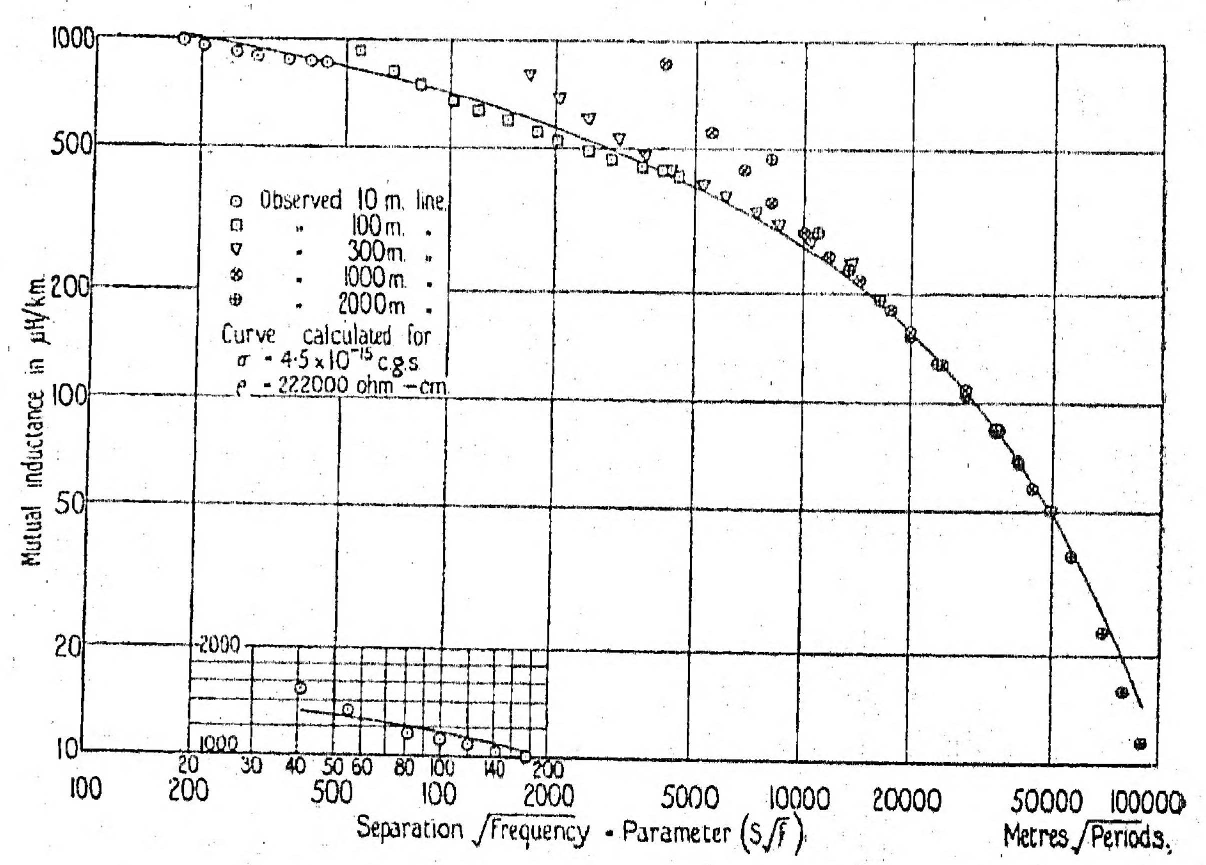


FIG. 8.—Mutual inductance as a function of $S\sqrt{f}$.

Referring to equation (1), we observe that the mutual inductance is a function of [separation × √(frequency)] for a given earth resistivity, so that, if plotted against this parameter, results at different frequencies and separations should fall on one curve. That this was

largely the case at Shap (apart from the mutual-resistance correction) is shown by Fig. 8. This may be taken as a criterion of current flow according to the simple theory.

Measurements of the induced longitudinal voltage on telephone circuits were made in 1932 during heavy-current tests on the Carlisle–Lancaster 132-kV grid transmission line.* This line was supplied with fault current from the Carlisle end, and earthed successively at Penrith, Kendal, and Lancaster. For each of these conditions the induced voltage was measured at Carlisle on a test-wire earthed at Lancaster and forming part of a main Post Office open-wire trunk route between these towns. Special test lines carried on light poles were also constructed at three points along the route, and the induced voltage measured on these also. The special test lines were 1 km long and at 100 m separation from the grid. The results are given in Table 4.

TABLE 4.

Parallel	Length	Separation	Geological formation	Measured * resistivity	Induced voltage, volts per ampere	
					Calculated	Measured
	km	metres		ohm-cm		
Southwaite test-line ..	1	100	Sandstone	4 000	0·08	0·07
Shap test-line	1	100	Wenlock group (Coniston grits)	220 000	0·16	0·11
Burton test-line ..	1	100	Ludlow group†	25 000	0·11	0·09
Carlisle to Penrith ..	27	Varying up to 3 300	*	—	0·2*	0·13
Carlisle to Kendal ..	67		*	—	2·4*	1·4
Carlisle to Lancaster ..	91		*	—	3·3*	2·45

* The geological formations occurring along the route were: Red sandstone, 4 000 ohm-cm; millstone grit, 9 000 ohm-cm; carboniferous limestone, 10 000 ohm-cm; granite, 100 000 ohm-cm; Wenlock group (grits, flags, and slates), 220 000 ohm-cm; Ludlow group, 25 000–35 000 ohm-cm.
The induction on the long parallels was calculated in sections corresponding to these formations. The earth resistivity was measured by 4-electrode and search-coil methods.

† Kirkby Moor flags (chiefly).

It is seen that the measured values are lower than the calculated values throughout. This is partly due to the fact that with a high earth-resistivity, as at Shap, the earth wire carried a greater proportion (about 40 per cent) of the current than that allowed for, but the greater part of the discrepancy is due to withdrawal of the earth current by other conductors, notably the L.M.S. main line, which parallels the power line from Carlisle to Lancaster and carried 10 to 30 per cent of the current in various parts, and also by a 33-kV line with earth wire running from Carlisle to Penrith.

The following general conclusions can be drawn from the tests at Skillingaryd and Shap:—

(1) The theory of Carson and Pollaczek was satisfactorily verified in each case.

(2) There was no evidence of any change of earth conductivity with frequency. Such apparent changes as have been observed elsewhere are probably due to the variation with frequency of the depth of penetration of the current into a stratified earth.

Values of the earth resistivity found at Skillingaryd and Shap were both very nearly equal to 220 000 ohm-cm. Fig. 9 shows, for a frequency of 50 cycles per sec., the mutual inductance corresponding to this resistivity

* See Bibliography, (24).

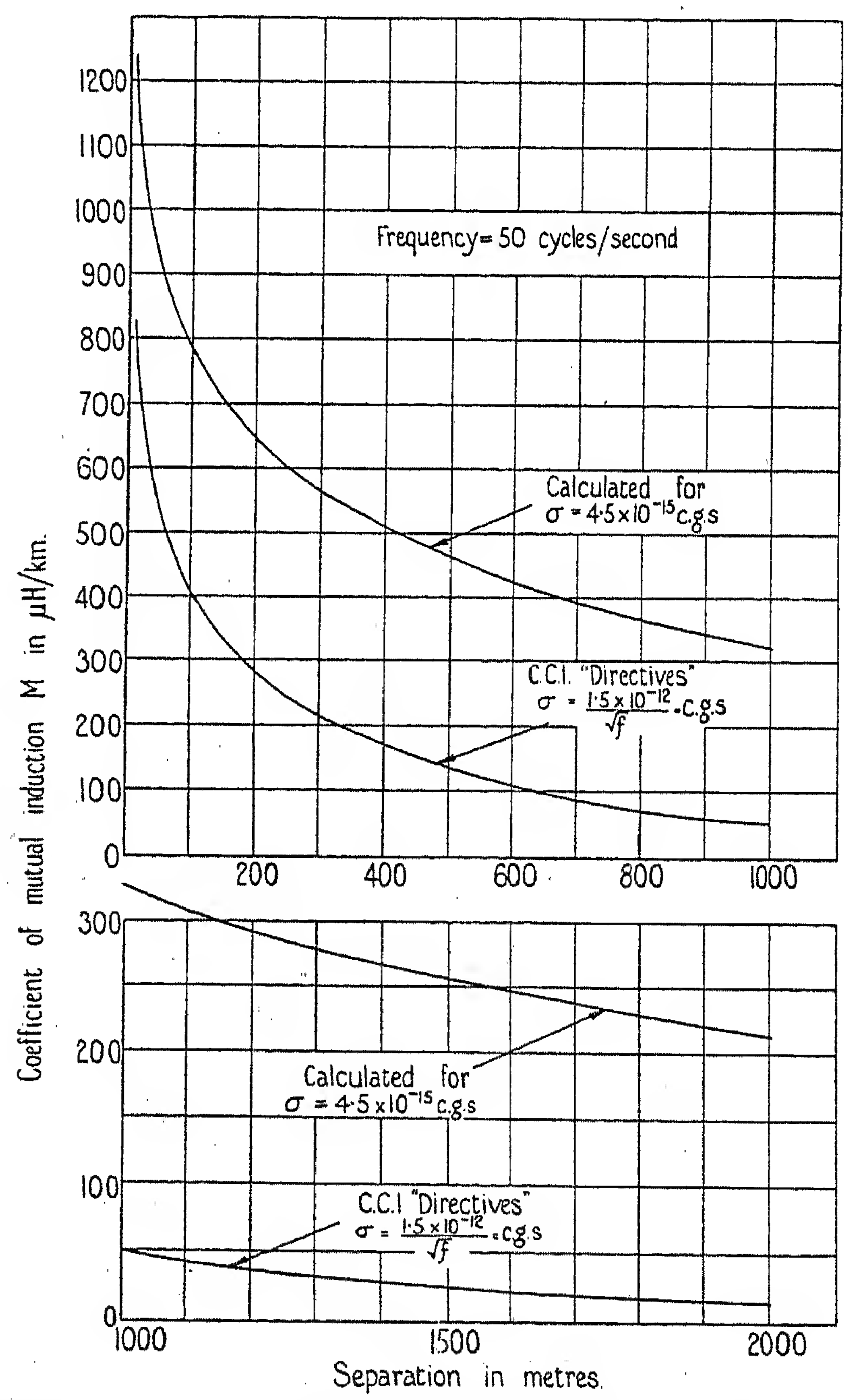


FIG. 9.—Comparison of measurements at Shap with C.C.I. " standard " values.

and also to the figure of 4 700 ohm-cm given by the C.C.I. for general use in non-mountainous country with 50-cycle current (from equation 3).

(ii) *Effect of Earth Wires.*—If a transmission line is provided with an earth wire, part of the residual current will return along this wire instead of wholly through the earth. Since the induction from the earth-wire current is negligible except for very close parallels, the induced e.m.f. is less than for a simple earth-return circuit and

the value obtained from the formulæ of the preceding section (i) must be multiplied by a screening factor λ, which is the ratio of the current in the earth to the total current. The theory of this has been given in a previous paper,* where it is shown that, neglecting end effects and capacitance effects:—

$$\lambda = (Z_1 - M_1)/(Z + Z_1) \quad . \quad . \quad . \quad (4)$$

In this formula Z is the impedance of the earth path, Z_1 the impedance of the earth wire, and M_1 the mutual impedance between earth wire and the conductor or conductors carrying the residual current, all the quantities being expressed in ohms per km.†

The screening factor does not vary much with earth resistivity. The variation with frequency is shown in Fig. 10 and is also not very marked. The resistance of the earth wire is important, particularly for power frequencies, e.g. for fault currents. With a steel earth-wire λ may be 0·9 or 0·95, but with steel-cored alumin-

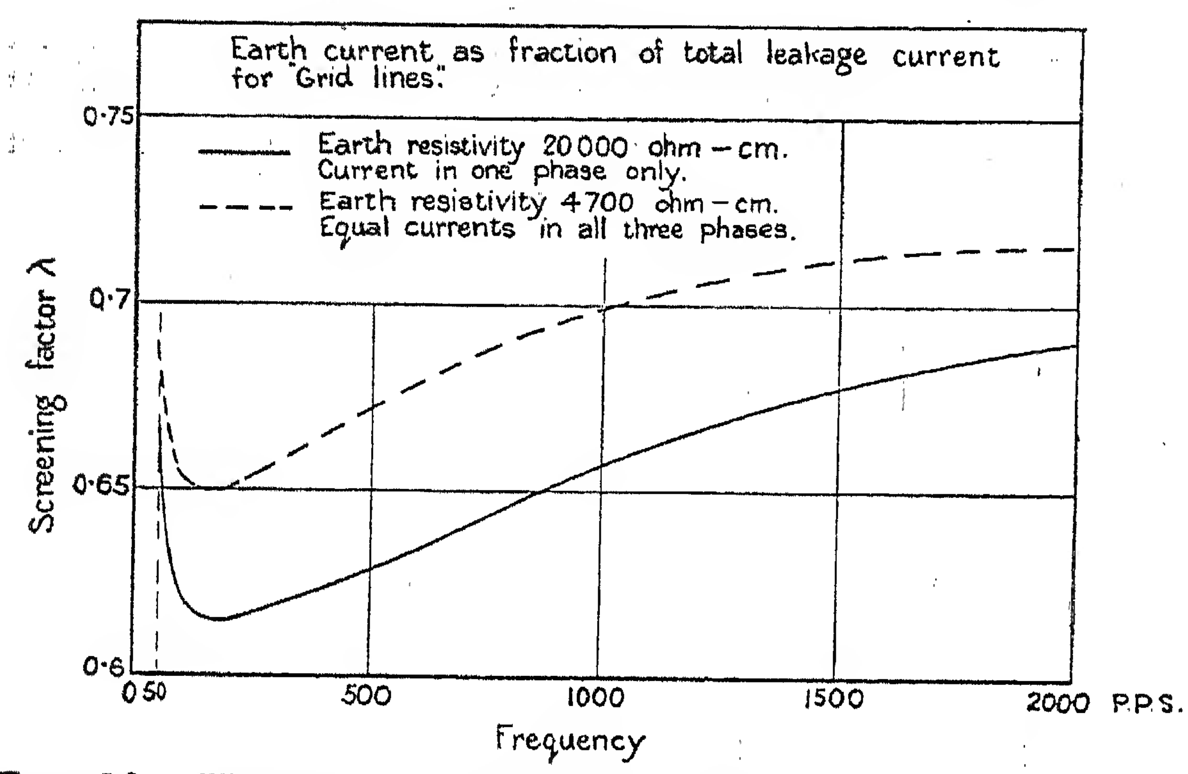


FIG. 10.—Variation of screening factor of earth wire with frequency.

ium (as on the C.E.B. system) λ is 0·67. It is uneconomical to decrease λ below about 0·65 by decreasing the earth-wire resistance, since two earth wires‡—one above and one below the conductors—are better from the point of view of cost, convenience, and utility in other directions, such as lightning protection. The induction may be reduced to one-third or one-fourth by this means.

Near a fault for power-frequency currents or near apparatus such as a transformer providing a path to earth for harmonic residuals, the distribution of current between earth wire and earth varies along the line when the earth wire is earthed at each tower, as is usually the case. If the fault path is direct to the tower or to metalwork in contact with the earth wire, the current in the latter will be large at the ends of the line, decreasing rapidly to the value given by equation (4) towards the middle. If the resistance to earth (including earth-electrode resistance) is R, while the resistance to the earth wire is negligible, then, at the end of the line

$$i/I = (1 - \lambda) + \left\{\lambda/\left[1 + (Z + Z_1)aR\right]\right\} . \quad (5a)$$

where i = earth-wire current, I = total current, $a^2 = G(Z + Z_1)$, G = conductance to earth of towers, in $\text{ohm}^{-1}\ \text{km}^{-1}$, and the other quantities are the same as in equation (4). If, on the other hand, there is a resistance R to the earth wire, the resistance to earth being negligible, i is small at the end of the line and increases towards the middle, its value at the end of the line being given by

$$i/I = (1 - \lambda) - \left\{(1 - \lambda)/\left[1 + (Z + Z_1)aR\right]\right\} \quad (5b)$$

The validity of equations (4) and (5) was proved by tests at Runcorn and Bedford,* already described, and

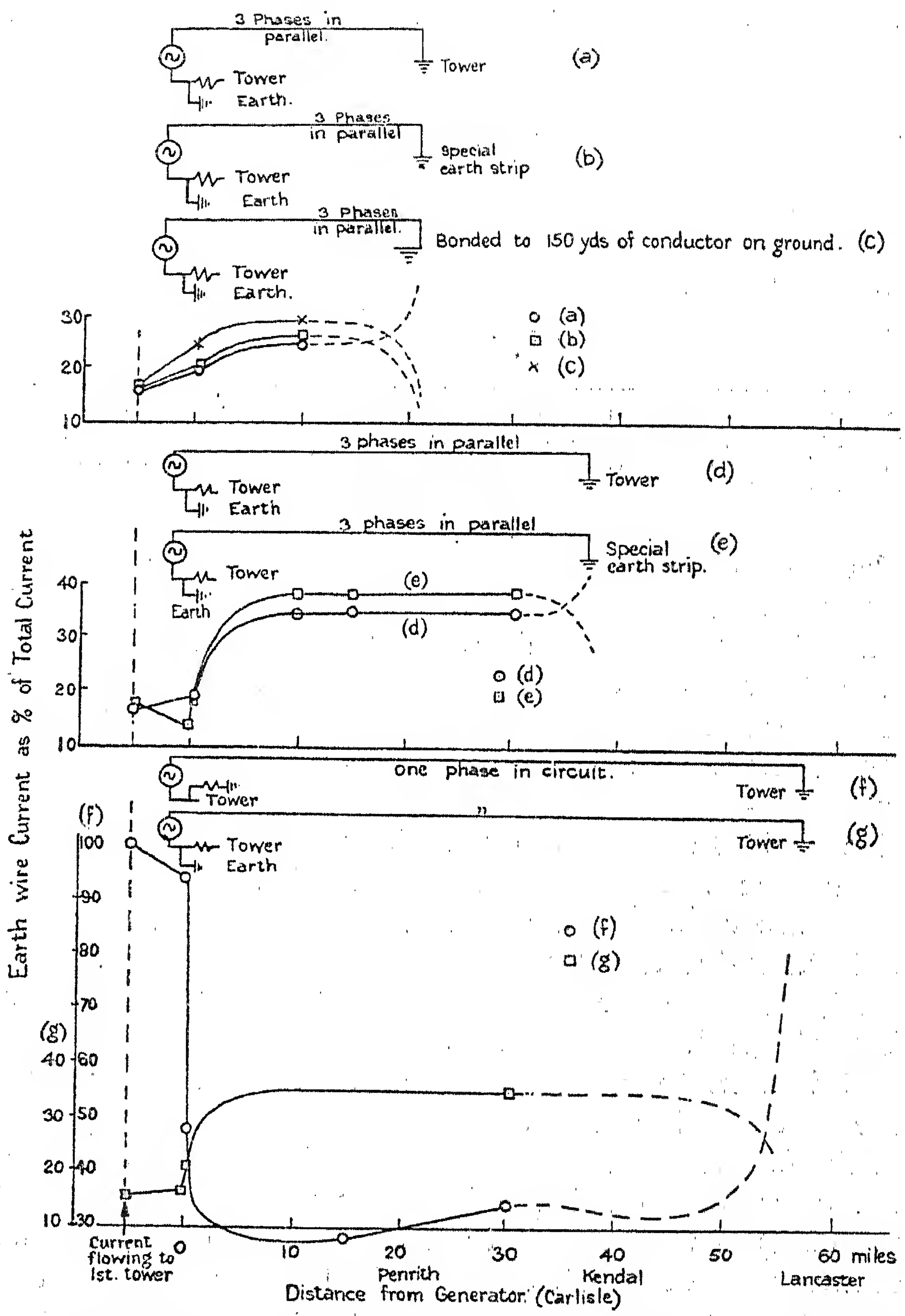


FIG. 11.—Variation of current along earth wire. (Test points taken from tests on Carlisle–Lancaster line.)

in more recent tests on the Carlisle–Lancaster line.† The latter results are shown in Fig. 11. The terminal conditions do not affect the average value of the earth-wire current (as in Fig. 11) unless the fault section is short. The use of an earth wire, however, ensures a low earth-resistance at every tower. This is illustrated in Table 5 (compiled from tests on one of the Central Electricity Board's lines).

This effect is of particular importance in mountainous regions of high earth-resistivity where, as in Westmorland, for example, the resistance of single-tower foundations has been found to exceed 50 ohms.

(iii) *Short-Circuit Calculations.*—Currents of power frequencies are chiefly of importance from the point of view of the possibly dangerous voltages which may be

* See Bibliography, (16).
† Formulæ for these quantities for numerical calculation are given in Appendix 1.
‡ See Bibliography, (16).

* See Bibliography, (15), (16) and (17).
† *Ibid.*, (24).

induced when an abnormal current flows in the system under short-circuit conditions. It is desirable, therefore, to mention briefly the chief method of calculation of such short-circuits, although, the subject being of great importance for other reasons, reference should be made for details to the extensive literature on the problem.

The main method is that of symmetrical co-ordinates in which the phase currents are analysed into three types: currents (i_0) which are equal and in phase in all three phases (zero-phase currents), balanced 3-phase currents (i_1) having a normal or positive sense of rotation, and balanced 3-phase currents (i_2) having the opposite or negative sense of rotation.

By drawing up the network of the system corresponding to each of these three types of currents, we may determine i_0, i_1, and i_2, in any branch in terms of the values of i_0, i_1, and i_2 at the fault. If Z_0, Z_1, and Z_2 are the corresponding impedances to the fault, then, at the fault:—

$$\begin{aligned} V &= \text{sum of partial voltages in phase } a \\ &= Z_0 i_0 + Z_1 i_1 + Z_2 i_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6) \end{aligned}$$

if V is the system voltage and i_0, i_1, i_2, are the partial currents at the fault. The most harmful type of fault

TABLE 5.

Tower earth-plate only	Tower foundations only	Earth plate and foundations	Resistance to earth of tower in service, with earth wire and earth plate connected
ohms	ohms	ohms	ohms
2·58	1·65	1·25	0·76
18·8	5·2	4·8	1·2
3·5	1·36	1·12	0·48
0·8	0·8	0·8	0·38

from the point of view of interference usually occurs when one phase is earthed. In this case, at the fault:—

$$\left.\begin{aligned} i_a &= I;\ i_b = i_c = 0 \\ \therefore\ i_0 &= i_1 = i_2 = I/3;\ \text{and} \\ I &= 3V/(Z_0 + Z_1 + Z_2) \end{aligned}\right\} \quad . \quad . \quad . \quad (7)$$

An example of such a calculation for a ring-main system is shown in Fig. 12* with some of the currents evaluated. The impedances of the branches are usually complex quantities and a considerable simplification results if phase rotations are neglected, that is, if the impedance of a branch is taken to be a reactance irrespective of its phase angle.† The networks are then equivalent to d.c. networks and can easily be solved by calculation or experiment. Again the positive and negative phase-sequence networks can usually be assumed to be identical, since the distinction mainly affects rotating machinery. These approximations do not lead to errors greater than 10 per cent, except where transmission lines are very long and a large number of branches must be taken into account.*

The short-circuit reactances of generating and transforming plant vary widely. The impedance of overhead lines, which is of importance in a system containing long lines, has been given in a previous paper,* but we may quote that for the C.E.B. single-circuit lines at 50 cycles per sec. the positive- and negative-sequence reactance is $0{\cdot}771\ \backslash\!\underline{20^\circ\ 30'}$ ohm per mile and the zero-phase reactance is $1{\cdot}73\ \backslash\!\underline{21^\circ\ 15'}$ ohm per mile (for an earth resistivity of 10 000 ohm-cm). A limiting resistance, Petersen coil, or other device, is often inserted in the neutral to limit the neutral current to some specified value such as 1 000 amperes. Such a value may then be taken for calculating interference under short-circuit

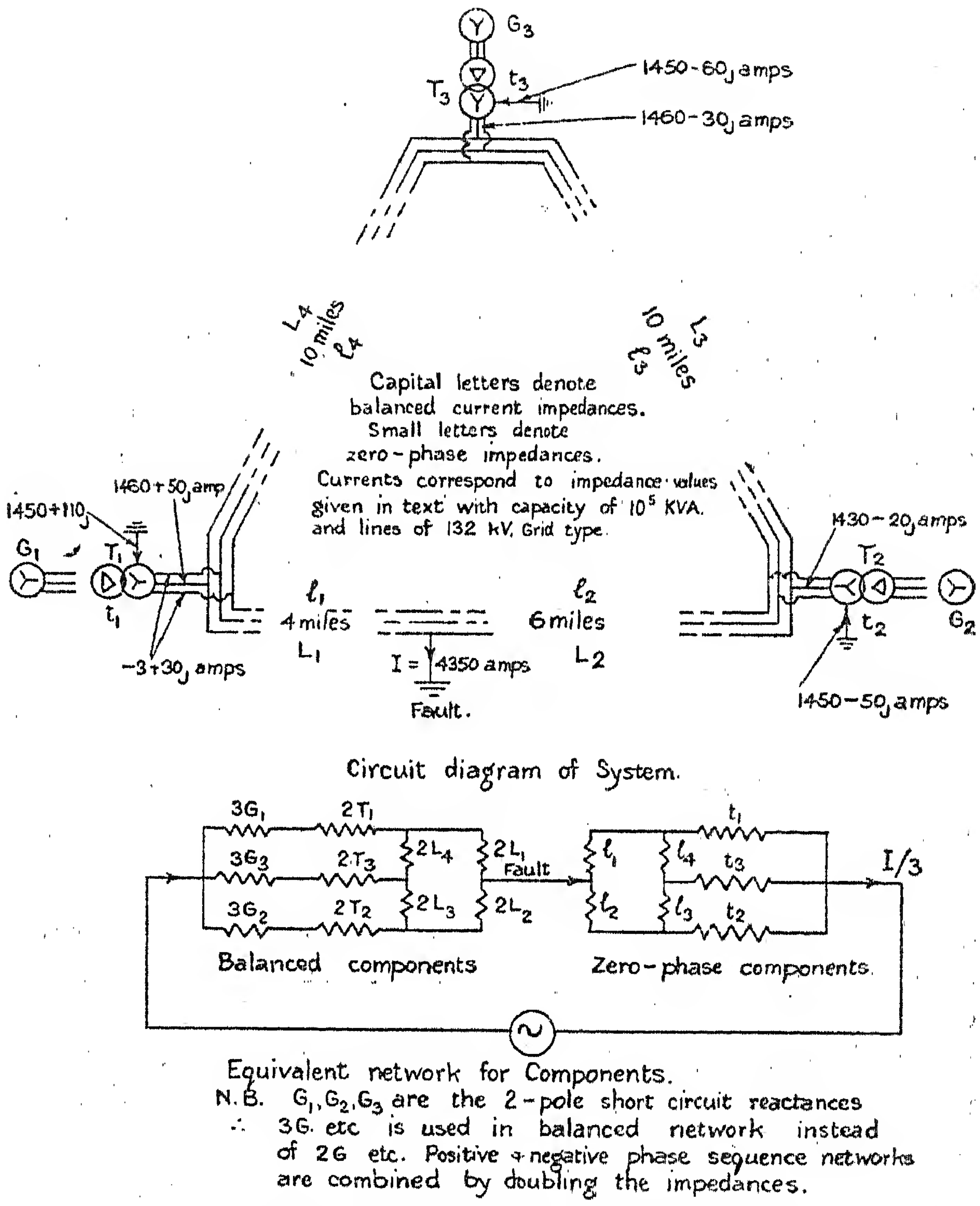


FIG. 12.—Example of short-circuit calculation by symmetrical co-ordinates.

conditions, but it is advisable to check by means of short-circuit calculations.

(iv) *Neutral or Residual Currents.*—We have already considered the class of neutral current arising from an earth fault and the problem of dangerous induction therefrom. The neutral currents occurring during normal operation are also a possible source of interference from induced noise owing to their harmonic content. The multiples of the 3rd harmonic are in phase on all three phase-conductors and will return through the neutral, including the earth in their path. Harmonics such as the 15th and 21st have high disturbance values, so that relatively small currents are troublesome. Other harmonics may arise from the wave-form of generators, distortion by transformers, corona on transmission lines, etc., and may be accentuated by resonance.

As far as multiples of the 3rd harmonic are concerned, the power system is equivalent to a single-phase system

* See Bibliography, (25).

† *Ibid.*, (18).

* See Bibliography, (16).

with earth return; transformers, etc., form intermediate and terminal impedances, and the transmission constants of the lines must be taken into account. Collard* has indicated that the calculation is greatly facilitated by the replacement of lines and transformers by their equivalent T networks. Fig. 13 shows a transmission line closed by transformers, the transformer on the left representing the supply and that on the right the load. A delta connection is represented by short-circuiting the network at the point corresponding to the winding. Point 5 represents the earth, so that if, for example, the secondary star point of transformer 1 were earthed, points 3 and 5 would be connected. P, M, and S, are the primary, secondary, and mutual impedances of a transformer, A and B being the impedances characteristic of a line. By forming such networks the neutral current can be evaluated for any branch, and the induced noise may then be calculated by the formulæ given in the paper, provided e and ke (k is the transformer ratio)—the harmonic voltages arising from the supply wave-form and transformer distortion—are known.

One of the most important problems in practice is the effect of earthing the neutral of a system at any given point. Collard has shown, using the above methods, that the effect may increase or decrease the

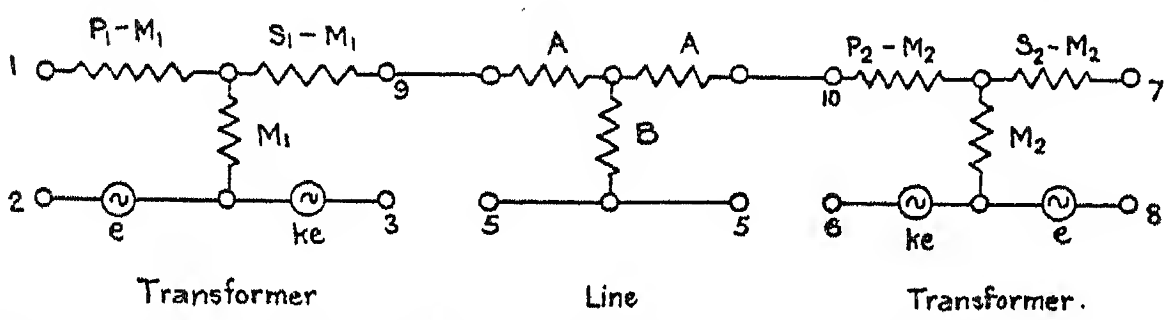


FIG. 13.—Equivalent T network for harmonic circuit of a line closed by transformers.

neutral current according to the nature of the system and the points already earthed. Although multiples of the 3rd harmonic are usually increased by earthing the neutral at the remote end of a line, this effect may be reversed in the case of long lines (more than $\frac{1}{4}$ wave-length†) and high frequencies.

In the tests at Portobello‡ on the harmonic composition and magnitude of the neutral current at a typical grid station, the neutral currents were small, not exceeding 3 or 4 amperes. The 3rd and, to a less extent, the 5th, formed with the fundamental the majority of the current. The multiples of the 3rd were not prominent, but a 17th harmonic appeared when power was exported. It was concluded that with neutral currents of the order and type observed, interference due to them would not be serious with the parallels likely to occur. Although the conditions did not admit of a fully loaded system or of variation of earthing at different parts of the system, the results were reassuring as to the harmful effects of a large system with direct multiple earthing.

Serious neutral currents are likely when the characteristic impedance of the system is small for a certain harmonic, particularly a multiple of the third. The capacitance of a cable system to earth in series with the inductance of directly connected and earthed generators is a simple example. Tests on such a system have been described elsewhere.* The system was found to resonate between the 9th and 15th harmonics, with the result that, although the voltage wave-form was good, these harmonics were large and caused disturbance.

In alleviating trouble due to neutral currents, regard must be paid to the cause. If it arises from resonance with certain multiples of the 3rd harmonic or a harmonic prominent in the voltage wave, then wave-traps in the neutral may be used which have a high harmonic impedance but a low impedance for the fundamental, to avoid voltage-rises on short-circuit. If the resonance frequency is low† a reactance can be used which, by reducing the resonance frequency, will increase the harmonic impedance but not the fundamental impedance. A resistance may also be used, but is difficult of design in respect of short-circuit duty. In systems where simple resonance is not important a reactance or resistance may be used, but reduction of neutral currents may also be achieved by earthing at selected points, particularly with ring-main systems. Earthing-compensators and transformers reduce harmonic currents without offering a high short-circuit impedance, but may be too costly or unsuitable to the system design. Provided it does not itself distort the wave, a transformer with a delta on the supply side prevents the circulation of harmonic residuals to a large extent.

(v) *Voltage-Rises near Earth Electrodes.*—Near a fault or near a neutral earthing point the lines of flow of residual earth-currents converge and a potential distribution is set up such that neighbouring conductors may be exposed to important potential differences. These are largest in the case of pilot cables laid in the same trench as power cables or in close proximity, but this risk is inevitable since the incidence and nature of the fault cannot be predicted.

A communication cable entering a substation or central station, but widely separated from the power system elsewhere, is only exposed to the potential distribution near the station. Using an earth tester or a potentiometer, and an auxiliary electrode at a sufficient distance, the equipotential lines round the station earthing-system may be plotted. Each equipotential line corresponds to a resistance R_n, found from the measurements, the general body of the earth being taken as zero and the metalwork of the station corresponding to its earth resistance R. If I is the fault current assumed, then R_nI is the maximum voltage appearing outside the equipotential line (n), RI being the highest possible voltage. Accordingly, if these voltages are large, it may be necessary to apply additional insulation to communication cables within the area bounded by a certain equipotential (n) and to safeguard connected apparatus. R may vary from a small fraction of an ohm for central stations and large modern outdoor substations to an ohm or more for small substations under unfavourable conditions. This matter is under investigation by the E.R.A.

(*b*) *Induction from Cable Systems.*

The cable sheath carries a part of the residual current, so that the current flowing in the earth and, consequently,

* See Bibliography, (19).
† About 30 miles for a grid line, zero-phase currents, at 1 050 cycles per sec.
‡ See Bibliography, (26).

* See Bibliography, (20).
† If the resonance frequency is high a reactance will increase the disturbance, but trouble would probably not arise in any case since a high resonance-frequency usually means a high impedance to harmonics.

the interference, are reduced. At a distance from the cable a few times its depth the earth current is distributed in the same way as with an overhead line. Fig. 14, which illustrates this, is taken from measurements on the Woolwich–Eltham cables (two 3-core 33-kV armoured type).* Having reference to the total residual current, mutual inductances were first measured on special circuits parallel to the cable, and were then corrected

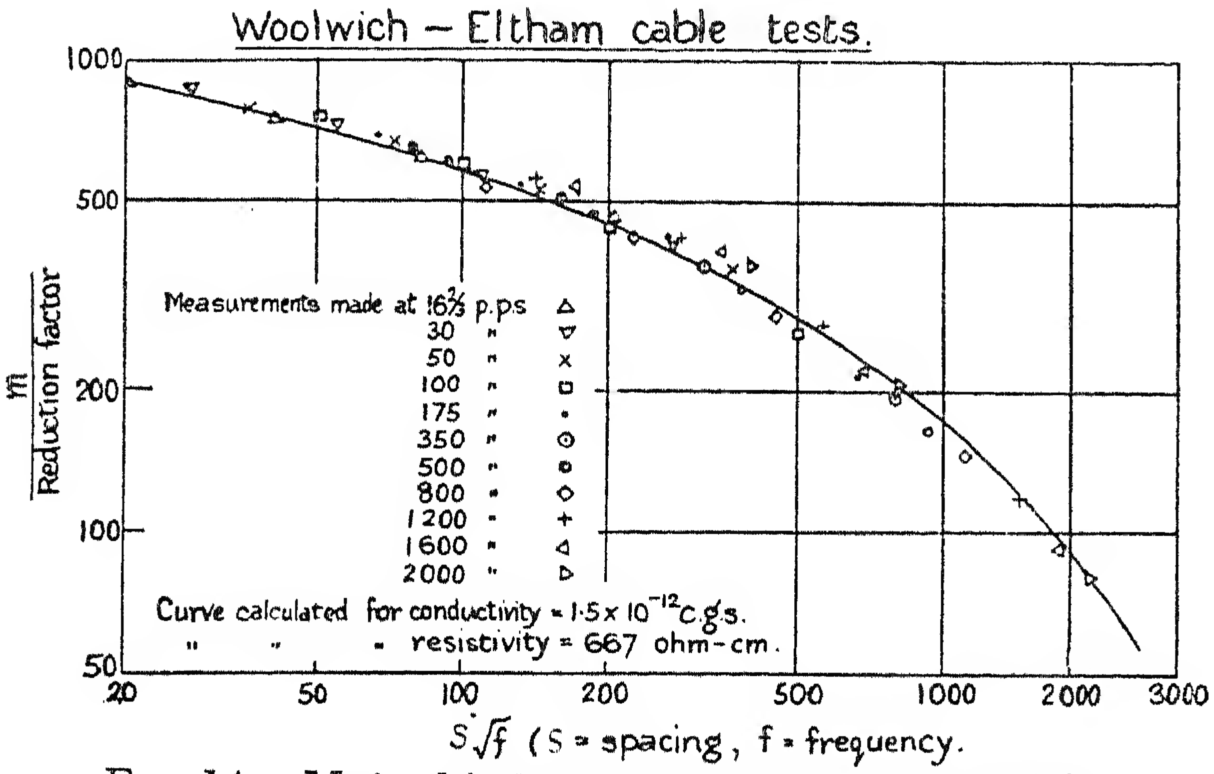


FIG. 14.—Mutual induction as a function of $S\sqrt{f}$.

experimentally for the fact that the earth current is a proportion, varying with frequency, of the total residual current. If a suitable factor is chosen for each frequency the points fall on the theoretical curve for an earth conductivity of $1 \cdot 5 \times 10^{-12}$ C.G.S. units (resistivity 667 ohm-cm). This value was in agreement with induction tests and with a 4-electrode resistivity survey.

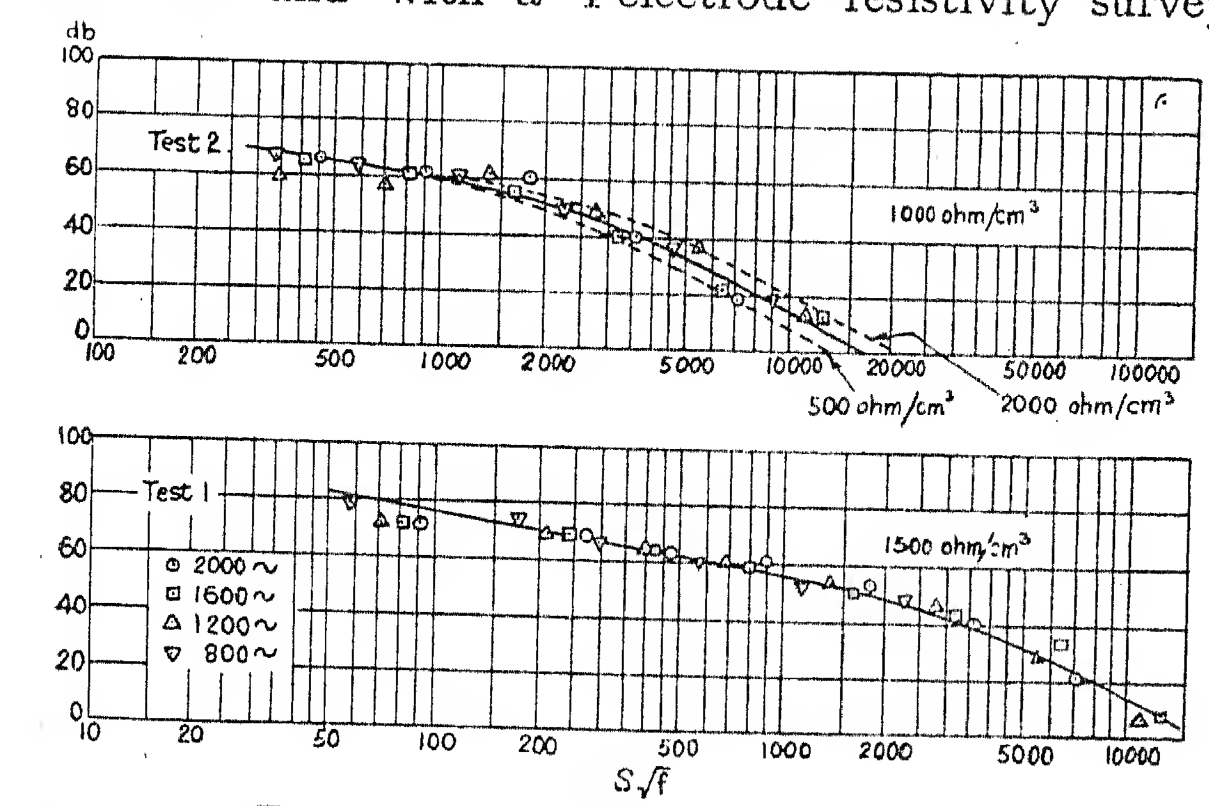


FIG. 15.—Search-coil measurements.

Fig. 15† shows search-coil tests made simultaneously by Collard, treated in the same way.

Since the distribution of current in the earth is similar to that for an overhead line, the induction may be calculated as in Section 3 (*a*) (i), with the inclusion of a factor λ to take account of the screening action of the sheath. λ may be found from an expression similar to equation (4), namely

$$\lambda = (Z_1 - M_1)/(Z + Z_1) \quad . \quad . \quad . \quad (8)$$

where Z and Z_1 are the impedances of the earth path and the sheath respectively, and M_1 is the mutual impedance between the sheath and core, or cores, all being expressed in ohms per km.*

Fig. 16 shows the calculated and observed screening factors from the tests on the Woolwich–Eltham cables. The discrepancy at higher frequencies is due to the neglect of capacitance effects which decrease the total current as one proceeds from the sending end, and

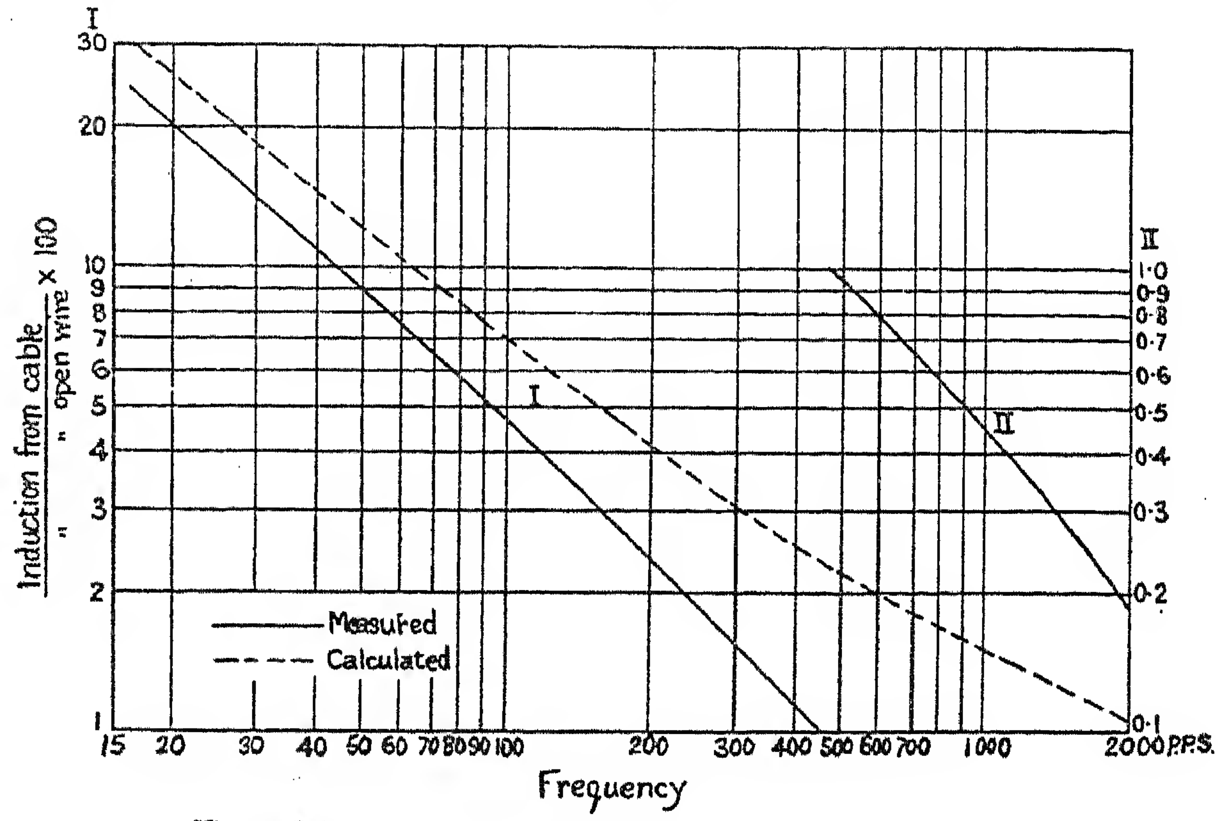


FIG. 16.—Screening factor of cable sheath.

increase the sheath current relatively to the earth current by producing a series of end effects along the length of the cable. The rigid calculation of these effects is very complex and generalization is difficult.† In practice, they will generally be found to give an error on the side of safety. With unarmoured cables λ is nearly inversely proportional to the frequency, but

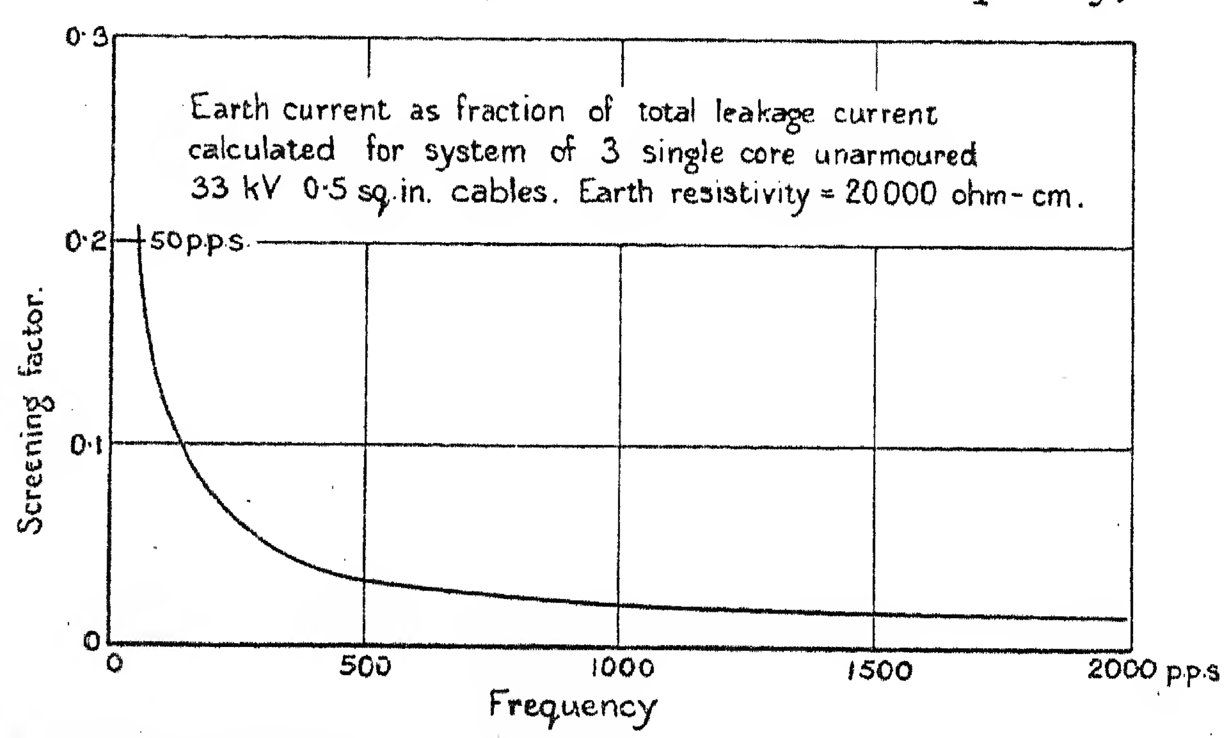


FIG. 17.—Variation of screening factor of plain lead cable-sheath with frequency.

decreases less rapidly at higher frequencies as shown by Fig. 17.

As λ becomes very small for harmonic frequencies,

* See Bibliography, (11).

† The values of the earth resistivity are not quite the same, since the search-coil tests were made at greater separations and refer to deeper and more distant strata.

* Formulæ for these quantities are given in Appendix 1, but for armoured cables laboratory tests on short lengths are often easier than calculation.

† An approximate formula for the screening factor, as modified by these effects, is:—

$$\lambda = \frac{Z_1 B}{Z}\left\{\frac{\alpha\beta}{\beta^2 - \alpha^2}\frac{\sinh \alpha l}{\sinh \beta l}\cosh \beta x + \frac{\beta^2}{\beta^2 - \alpha^2}\cosh \alpha x\right\} + \frac{Z_0}{Z}\left\{1 - \beta \cosh \alpha l\right\}$$

where

$$B = \left\{Z_0(Z + Z_1) - ZZ_1\right\} / \left\{(Z + Z_1)(Z_1 + Z_0)\right\};$$

$\alpha^2 = C\omega j(Z_1 + Z_0)$; $\beta^2 = GZ$;
Z_0 = core impedance per cm;
Z = sum of earth impedance and mutual impedance of core and sheath per cm;
Z_1 = difference of sheath impedance and mutual impedance of core and sheath;
G = sheath leakage to earth per cm;
C = capacitance per cm;
l = total length of fault section; and
x = distance from fault.

disturbance during normal operation from harmonics is on the whole less important than dangerous induction during faults. Table 6 gives the calculated order of λ at 50 cycles per sec. for the more usual types of systems.

The effect of earth resistivity on λ is not large at 50 cycles, but magnetic saturation of steel armouring may be important with heavy fault currents. No such effects were observed with residual current up to 250 amperes during tests on the 3-core 33-kV cable previously referred to. λ is increased by the use of reactor bonding with insulating sleeves. For example, for three 1·0-sq. in. single-core 6·6-kV unarmoured cables λ would increase from 0·1 to 0·4 if reactors replaced plain bonds.

End effects are not usually important with cables, the sheaths of which are generally well earthed along the whole route so that the current is rapidly divided between sheath and earth. In the event of a fault or leakage occurring outside the cable section, the sheath of which is not specifically bonded to earth, the earth current will be given by equation (8) over the middle of the section, but will be greater at the ends. Apart from the increase in λ, special methods of sheath bonding only affect conditions near a fault, where considerable e.m.f.'s (100–200 volts) may appear at the bonds.

TABLE 6.

Type of cable system	Screening factor (λ)
One 3-core armoured cable (< 6·6 kV)	0·2–0·4
One 3-core armoured cable (11–66 kV) (0·2 to 0·3 sq. in.)	0·15–0·3
Two 3-core armoured cables (11–66 kV) with sheaths bonded in parallel ..	0·075–0·15
Three single-core unarmoured cables (< 6·6 kV) (0·3–1·0 sq. in.) ..	0·15–0·25
Three single-core unarmoured cables (6·6–33 kV) (0·3–1·0 sq. in.) ..	0·05–0·2

(c) Interference from Traction Systems.

Ordinary rail-return tracks are equivalent to single-phase power systems with earth and rail return. The mutual inductance may therefore be calculated by the ordinary formulæ of Section 3 (*a*) (i), with a screening factor λ which allows for the compensating effect of the rail currents. This factor is given by

$$\lambda = Z_1/(Z + Z_1)^* \quad . \quad . \quad . \quad . \quad (9)$$

where Z_1 is the impedance of the rails and Z the impedance of the earth path. Generally speaking, we may take the impedance of n rails in parallel as $(1/n)$ times the impedance of one. End effects may usually be neglected, both as regards those due to exchange of current between earth and rails near the train and those due to exchange between adjacent tracks.† These effects do not extend beyond $\frac{1}{4}$ to $\frac{1}{2}$ mile. The bonding of the rails is of great importance. Figures quoted by the C.M.I. showed that the reduction of joint resistance by special bonding from 2 000 to 350 microhms reduced the interference by from 10 to 46·5 per cent with one and four lines of rails bonded respectively (double-track line). Increases of frequency and current density increase the rail current with unbonded rails due to permittance and cohesive effects respectively.

For the 2-track Manchester–Altrincham railway,* calculation of λ with a measured earth resistivity equal to 10 000 ohm-cm gave values of 0·23 at 300 cycles per sec., increasing slightly to 0·27 at 1 800 cycles per sec. Noise measurements indicated that the earth current was about 20–25 per cent of the total, and agreed with calculation that the screening factor did not change much with frequency. Continental tests have given values higher than this, i.e. values for λ up to 0·5 or 50 per cent earth current, but it may, in the opinion of the authors, be assumed that λ will lie between 0·2 and 0·4 for British practice with a double track. Tests in Germany† on a third-rail system gave a value for λ of 0·2 varying only to a small extent with frequency, which is in agreement with calculation. λ is larger for tramways owing to higher rail resistance and less efficient bonding, but is unlikely to exceed 0·6 for a double track or 0·8 for a single track.‡

As already stated in Section (2), low-frequency ($16\frac{2}{3}$ cycles per sec.) traction plant has a low disturbance value, but all the currents are residuals since the system is single-phase. The induction may be readily calculated from the formulæ, knowing the T.I.F. of the generating plant, etc. Induction from the fundamental may also be important, particularly during the starting of trains. Direct induction is important for circuits run along the track.

Induction from d.c. railways mainly arises from the harmonics produced by the power plant, rotary convertors, motor-generators, or mercury-arc rectifiers. These harmonics will circulate in the track and earth wherever there is a connection between them and the contact line. Such a connection may be provided by a train, or by converting plant or the resonant shunts of mercury-arc rectifiers at distant substations. With third-rail systems capacitive leakage also occurs, but will not be great except with large systems. If the power plant gives an assemblage of harmonics of voltage e_n at frequencies nf (f = supply frequency), the noise e.m.f. e induced in a communication circuit will be given by

$$e = k\lambda l\sqrt{\left\{\Sigma(n\alpha_n 2\pi f e_n M_n/Z_n)^2\right\}} \quad . \quad . \quad (10)$$

where l = length of parallel, M_n = mutual inductance between earthed circuits at frequency nf, Z_n = impedance of the rail system at this frequency, and k is a factor depending on the balance of the communication circuit [discussed in Section 3 (*d*)]. For earthed circuits, $k = 1$: α_n is the noise weighting factor already discussed in Section 1 (*a*). We shall first illustrate this formula

* Detailed formulæ are given in Appendix 1.

† For an analysis of this, see *Bulletin Oerlikon*, Nos. 132, 133 (June and July, 1932); also PLEIJEL and HOLMGREN: Swedish Committee report, tr. Kuntze (Oldenburg, Munich, Berlin); and T. MULLER: *S.E.V. Bulletin*, 1929, vol. 20, p. 220.

* See Bibliography, (12). † *Ibid.*, (21).

‡ For recent types of tracks with welded rails, λ may be about 0·4 and not increase very much with frequency. Nevertheless for old tracks and under unfavourable conditions as to joint resistance λ might be as high as 0·95 for power frequencies, decreasing to 0·6 or 0·7 at high frequencies.

from results (Table 7) obtained in the tests at Manchester on a mercury-arc rectifier.

TABLE 7.

Load = 1 500 amperes from four 6-car trains, braked.
Mercury-arc rectifier supplying total load—filters removed.
Earth resistivity = 10 000 ohm-cm. $\lambda = 0\cdot2$.

Frequency of harmonic	Measured current	Calculated coefficient of mutual induction to P.O. earthed circuit	Induced voltage per km in test circuit	Weighted value (in volts per km) at 800 cycles per sec.
	amperes	μH per km	volts	
300	14·0	775	4·10	1·31
600	3·3	700	1·74	0·97
900	2·3	665	1·73	2·44
1 200	1·0	640	0·96	1·21
1 500	1·0	620	1·17	0·49
1 800	1·0	600	1·27	0·36

Calculated overall disturbing voltage (from above Table) = 3·23 volts (at 800 cycles per sec.) per km = 7·6 volts for the circuit (1·46 miles).

Observed disturbing voltage = 7·1 volts at 800 cycles per sec.

The variation of M_n with the order of the harmonic is much greater for circuits at some distance from the railway. The relative importance of a given harmonic therefore changes with the separation, and so will the apparent efficacy of a device suppressing it. For example, tests on the rectifier-fed railway already referred to* showed that suppression of the 1 200-cycle ripple made no difference to noise measurements at a separation of 1 000 metres from the track.

If the harmonic distribution is fairly constant for a given class of power plant (as with mercury-arc rectifiers), then, to a first approximation, M_n may be replaced by an average value M having an appropriate variation with separation. Equation (10) then reduces, if the system is mainly inductive, to

$$e = k\lambda lMVE'/(100L) \quad . \quad . \quad . \quad . \quad (11)$$

where L is the system inductance, V the system voltage, and E' the T.I.F. expressed as a percentage, using normal weighting values. If the system is mainly resistive, with a resistance R, then

$$e = 50\, k\lambda lMVE''/R \quad . \quad . \quad . \quad . \quad (12)$$

where E'' is the T.I.F. expressed as a percentage, with the frequency factor included in the weighting. Fig. 18 shows the variation of M for a mercury-arc rectifier without shunts. This is expressed as a fraction m of the mutual inductance at close spacings, which is nearly constant (about 900 μH per km). A very rough but convenient formula for British practice, using rectifiers without shunts, is

$$e = 2\, kVm \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

e being measured in mV per km at 800 cycles per sec. and m being taken from Fig. 18 according to the separation.

* See Bibliography, (12).

For circuits run along the track, direct induction from the conductor as well as the effect of earth currents is important. The relative situations of the conductors of the different systems are much the same for most railways, apart from the distinction between overhead feeders and third-rail. In the tests made at Faugères on the overhead system on the Midi railway with 1 500-volt rectifiers it was found fairly consistently that when the harmonics in the output from a rectifier without filters could circulate in the traction circuit, either by way of a train or by convertors or generators feeding the system elsewhere, or by the filters of another rectifier also feeding the system, the induction in a circuit on poles along the track was 1·5–2 mV per km at 800 cycles per sec., the circuit having short transpositions and being balanced with respect to earth to less than 1 per cent. To allow for longer untransposed lengths and unbalances to earth up to 4 per cent, it is better to assume an induced noise

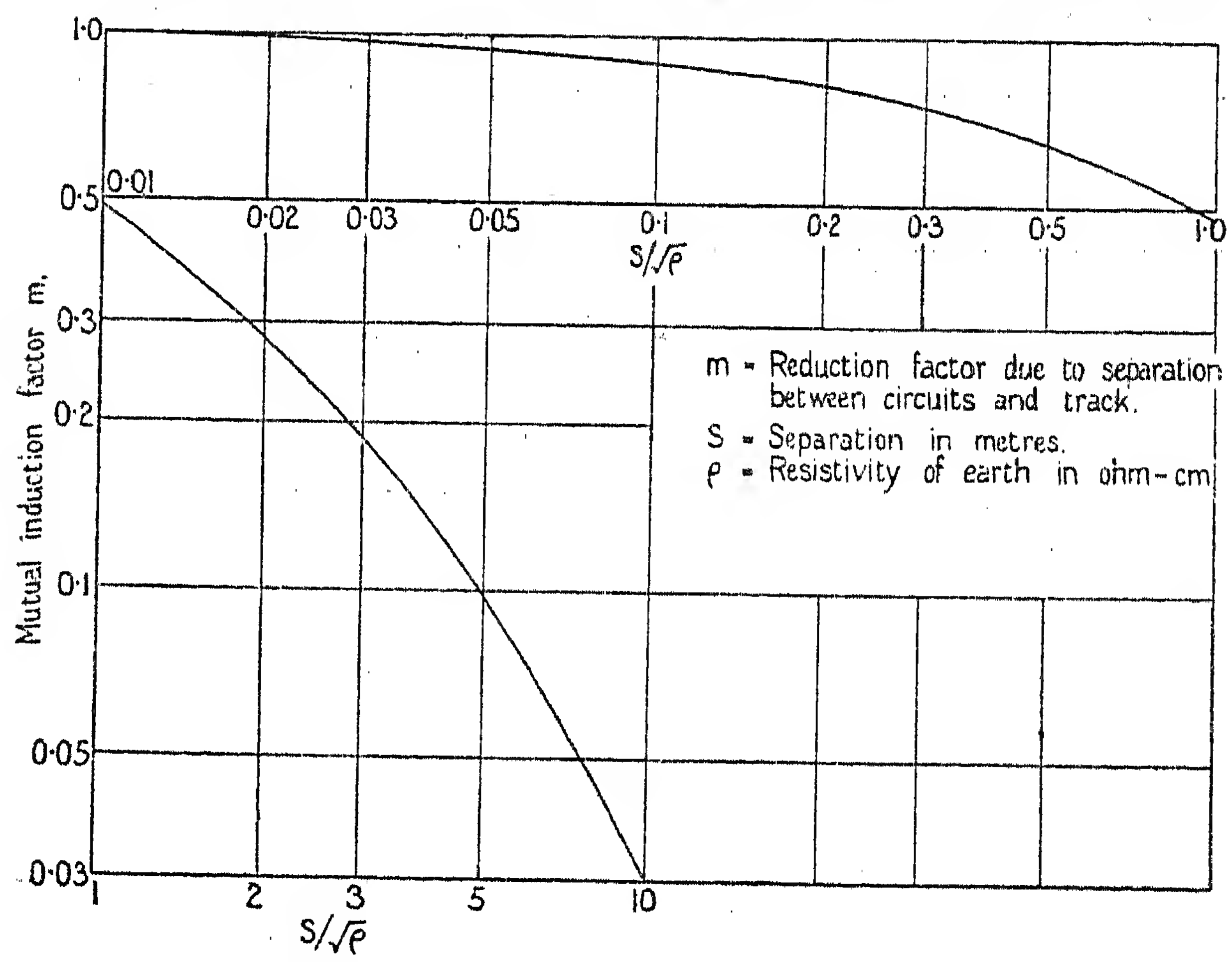


FIG. 18.—Interference from traction systems: effect of separation and earth resistivity on induction from mercury-arc rectifier without filters.

of 7 mV per km at 800 cycles per sec. The noise would be roughly proportionately greater for a higher-voltage system or less for a lower-voltage system, and would probably be reduced still further in the case of a third-rail system.

The use of resonant shunts with mercury-arc rectifiers reduces the disturbance to one-fifth or one-tenth according to the separation; such equipment and good rotary convertors (T.I.F. 0·5 per cent) will therefore be satisfactory except in very severe cases. Filters may sometimes be dispensed with, but regard should be paid to the system as a whole, including the nature of other substations.

(d) Transverse Induction, Effect of Unbalance.

(i) *Transverse Induction.*—Within a telephone cable the two wires forming a pair are twisted together with a very small separation, so that the longitudinal voltages induced along them will be exactly equal. In the case of open-wire circuits, there is considerable separation between the two wires of a pair, so that close to the source of induction a transverse voltage equal to the difference between the two longitudinal voltages is

induced. The transverse voltage is obtained from the coefficient of the mutual induction in the loop, M_d. M_d is given, in μH per km, by

$$M_d = 200\,\Delta x/x \quad . \quad . \quad . \quad . \quad (14)$$

where Δx is the horizontal separation in metres between the wires composing the pair, and x the separation in metres between the telephone pair and the power circuit. In practice, the transverse induction is reduced by transposition of the telephone conductors. Transposition on the symmetrical-twist system gave good balance to an outside power source, but, owing to cross-talk between the telephone circuits, has been replaced in this country by a standard system of cross-overs. With the present system and the most unfavourable location of the source of induction, one circuit out of a large group may be left with an untransposed exposure up to 2 miles in length.

(ii) *Unbalance.*—Even in the event of both wires of the telephone circuit being uniformly exposed to the disturbing line, disturbing currents may be caused to flow unless both wires are perfectly balanced as regards series impedance, capacitance, and leakage to earth. Apparatus which has been developed for measuring the unbalance of telephone lines is described in the C.C.I. Directives.* As a general expression the unbalance may be represented by the value

TABLE 8.

Percentage unbalance added (defined by equation 15)	Measured noise voltage per 1 000 amperes railway load	
	Test 1	Test 2
	mV	mV
0	<2·0	<2·0
5	5·2	4·1
10	9·1	8·3
15	13·4	12·7
20	16·4	16·5

$$u_e = (R_a - R_b)/\left[\tfrac{1}{2}(R_a + R_b)\right] \quad . \quad . \quad . \quad (15)$$

where R_a and R_b respectively are the impedances of the "a" and "b" wires to earth. The C.C.I. Directives allow a maximum permissible unbalance to earth of 4 per cent for open-wire lines, but such measurements as have been made indicate that the unbalance of British lines is very much less than this. No definite relationship has been established between the longitudinal voltage induced in a circuit, its unbalance, and the noise voltage measured across it. This problem is under investigation by the C.M.I. Table 8 gives the result of measurements made on a short open-wire line to which artificial unbalances were added by bridging a non-reactive resistance across the line and connecting an intermediate point to earth. The circuit was transposed on the continuous-twist system, and induction was from a railway supplied by mercury-arc rectifiers without shunts.

In Test 2 the added unbalances were reversed with respect to Test 1.

For cable circuits an unbalance not exceeding 1 per cent is specified provisionally by the Directives. Other considerations than power interference, however, render necessary the reduction to a minimum of all unbalances between wires in main cables. Immunity from power disturbance under quite severe conditions is obtained without special reduction of the unbalance which produces noise due to external induction. This is the "direct" capacitance unbalance of the circuit to the next outer layer or to the sheath.*

(*e*) *Screening Effect of Telephone Cable Sheaths.*

Telephone circuits contained in cable are completely screened from electric induction and partially screened from magnetic induction. Magnetic induction sets up a longitudinal e.m.f. along the cable sheath. This causes a sheath current to flow which partly compensates the effect of the direct induction on the conductors within.

The screening factor (λ) of the sheath is the ratio of the induced longitudinal e.m.f. in the cable conductor to that which would be induced in an open line in the same position. Longitudinal induction within the cable is therefore calculated by multiplying open-wire values by this factor. It can be shown that, to a sufficient degree of approximation,†

$$\lambda = R_s/(R_s + j\omega L_s) \quad . \quad . \quad . \quad . \quad (16)$$

where R_s is the resistance of the sheath and armour, and L_s the self-inductance of the sheath circuit with its earth return.

At the frequency of the fundamental, R_s equals the d.c. resistance of sheath and armour. At harmonic frequencies, there must be added to R_s in the denominator only of equation (16) the resistance of the earth return, which is usually small [$(\pi\omega/2) \times 10^{-4}$ ohm per km, approx.], together with the power loss in the armouring.

L_s is composed of two parts—the inductance of the earth return and the inductance added by the sheath armouring, if present. The former is of the order of 2 mH per km, and varies very little with the frequency or the resistivity of the earth.

In Great Britain practically the whole of the underground telephone system consists of unarmoured cable, so that L_s is the inductance of the earth return only. On the other hand R_s falls rapidly with increased diameter and thickness of sheath, so that appreciable screening is obtained with the larger-size cables. Table 9 gives calculated screening factors for unarmoured lead-sheathed cables of various diameters as used by the British Post Office.

Owing to the inductance added by the steel, armoured cables afford a greater reduction in the induced voltage than unarmoured cables. To meet severe conditions in special cases on the Continent, cables have been constructed in which L_s has been increased by the addition of specially designed armouring of increased permeability; in other cases R_s has been reduced by means of copper wires under the sheathing.‡ A few armoured telephone cables buried directly in the ground

* See Bibliography, (1).

* See Bibliography, (28). † *Ibid.*, (21). ‡ *Ibid.*, (13).

are being laid in this country and will, from the point of view of interference, compare favourably with cables of equal diameter laid in the standard manner.

Measurements of the screening factor given by an unarmoured lead-sheathed cable 2·7 in. diameter, contained in a cast-iron pipe, were made during tests on the Carlisle–Lancaster grid* line. Calculation gave a screening factor of the order of 0·1 for the combination of sheath and pipe. Comparison of the voltages measured on the cable circuit with those measured on an open wire following the same route indicated a screening factor equal to 0·14.

When several cables are laid close together, as in adjacent ways in a duct route, the induced voltage becomes influenced by the compensating currents in the various sheaths, so that calculation of the effects becomes impracticable.

TABLE 9.†

Diameter of cable	Screening factor	
	At 50 cycles per sec.	At 800 cycles per sec.
inches		
0·5	0·99	0·4
1·0	0·9	0·15
1·5	0·8	0·09
2·0	0·6	0·05
2·5	0·5	0·04
3·0	0·4	0·03

(*f*) *Effect of Rails on Railway Circuits.*

Earth-fault current from neighbouring power systems finds its way into the rails and acts inductively on circuits carried alongside the track. In addition, single-wire circuits operating block signalling instruments are usually earthed to the running rails. There is therefore a metallic loop in which an e.m.f. is induced and in part of which a current is flowing, giving an ohmic potential drop. Measurement has indicated, however, that the induced e.m.f. is several times greater than the ohmic potential drop.

Experiments have been made on circuits belonging to the Southern Railway at Southfleet, and on the L.M.S. Railway. At Southfleet, induction was from a 132-kV grid line paralleling the railway for a distance of 2·3 miles at a separation of about 160 yards, with a current of 160 amperes to an artificial earth fault. Calculating from the measured value of the earth resistivity (6 000 ohm-cm), with allowance for the screening effect of the earth wire on the grid line, the induced e.m.f. should have been 41 volts in the principal test circuit, in the absence of the rails. The measured values were from 11·4 to 12·3 volts, according to the type of earth connection used. Measurement showed, however, that the four rails were carrying a total current of 68 amperes, the inductive effect of which on the test circuit should have been 70 per cent greater than the direct effect of the grid line, owing to the closer coupling. Assuming the two effects to be roughly opposite in phase, and that the rail current fell to zero opposite each end of the energized section of the grid line, rough agreement was obtained between calculated and observed values.

Experiments made on the Lancaster–Carlisle grid line, which parallels the L.M.S. main line for 60 miles, showed rather similar results. The railway telegraphs were affected with earth currents of 10–30 amperes, but the instruments are relatively insensitive and the most serious disturbance was experienced on the block signalling system on the Shap section, where the earth resistivity was 200 000 ohm-cm and the separation of the order of 100 yards. Earth-return currents of 10–20 amperes closed the relays and locked the signals. About 20 per cent of the earth current appeared in the rails over this section. This particular case is probably the most severe to be encountered in Great Britain, exhibiting both a high earth resistivity and a close parallel.

The problem is so complicated by the effects of earth connections that precise calculations are impossible. The magnitude of the rail current itself will depend largely on the insulation of the track and the closeness of its approach to the fault point and substation.

If the rail currents are known, their inductive effects can be computed easily, as the coefficient of mutual induction to a line carried on poles alongside the track will not change greatly for comparatively wide changes in the earth resistivity, height of line, etc. It will generally be of the order of 1·4 mH per mile for each rail.

(*g*) *Measurement of Earth Resistivity.*

A more detailed discussion of this subject will be given in a separate paper, but owing to its importance in connection with interference a brief outline of the subject and the pertinent conclusions as to methods are given here.

(i) *Methods Available.*—(1) Alternating-current mutual-inductance measurements demand essentially parallel lines at a separation such that $s\sqrt{(f/\rho)} \geqslant 10$. Since for the calculation of the resistivity the magnitude of the induced voltage only is required, measurements may be made with a voltmeter. Economic considerations limit the use of this method. Recent work in the United States* has aimed at the development of a relatively simple testing scheme which could be used to determine an experimental coupling curve, using short-length disturbed circuits, and either an existing power or telephone line or a specially laid-out conductor as the disturbing line.

(2) Collard has devised a cheaper method utilizing the harmonics in an existing power line. The voltage induced in a search coil at various separations from the power line is amplified and measured, the measurements being made with a resonant circuit incorporated in the apparatus tuned to select different harmonics. The curve so obtained is compared with a series of theoretical curves calculated for different values of the resistivity,

* See Bibliography, (24).
† The figures given in this table have not been experimentally verified and should only be taken as indicating the order of magnitude of the screening.

* See Bibliography, (7).

and the resistivity most nearly coinciding with the experimental points is taken. The method was developed to meet the case where the communication line is second comer. If the conditions are reversed and an open-wire telephone line already exists, it is sometimes possible to supply this with the necessary high-frequency currents from a portable generator.

(3) Direct-current methods amount to a measurement with direct current of the mutual resistance R between two suitably chosen earth-return circuits. The resistivity is given by

$$\rho = 2\pi R \Big/ \left[\frac{1}{a_{13}} + \frac{1}{a_{24}} - \frac{1}{a_{14}} - \frac{1}{a_{23}}\right] \quad . \quad . \quad (17)$$

where current is fed into the earth at points 1 and 2 and the potential is measured between 3 and 4, a_{13} being the distance between electrodes 1 and 3, etc. Equation (17) can be utilized when a number of earthing points —not necessarily in a straight line—already exist and are connected to a central testing point. Measurements were made in this way on Shap Fells, using earth plates which had been sunk as terminations for lines laid down for mutual-inductance measurements (Fig. 6).

In a simpler form of test, the electrodes are spaced equally apart in the same straight line. Then, if a is the spacing between adjacent electrodes, equation (17) reduces to:—

$$\rho = 2\pi a R \quad . \quad . \quad . \quad . \quad . \quad . \quad (18)$$

It is possible, from a series of tests at different electrode spacings, to deduce the resistivities of an upper and lower layer, when the earth is roughly stratified in two layers.* Greater complexity makes accurate deduction almost impossible, and one is led to the empirical rule of Gish and Rooney that the apparent resistivity at a spacing a corresponds to the mean resistivity to a depth a. Difficulty is encountered on very low-resistivity sites, since the measurement of R with the required spacings then necessitates the use of large currents to obtain sensitivity, non-polarizable electrodes, and a compensating circuit for stray e.m.f.'s as in the Broughton-Edge (Tinsley) earth-testing potentiometer. Normally, however, polarization effects and stray e.m.f.'s may be eliminated by the use of the Megger earth-tester,* which employs pulsating current. With this instrument readings are obtained very easily, and the results are reliable provided R is large enough to give a satisfactory reading, e.g. 0·5 ohm or more.

It has been found that the values of earth resistivity determined from mutual-inductance measurements, search-coil tests, and 4-electrode tests, can be correlated within the limits of experimental error, and agree with the general geological structure.

(A) Of these three methods the first gives the resistivity corresponding to the important quantity to be measured in practice, namely the induced longitudinal e.m.f., but is expensive to carry out if two suitable lines are not already in existence. Where these exist, or where the expense is justified for special reasons, it is recommended that mutual-inductance measurements should be made.

(B) Where the necessary alternating currents from a line are already present in the earth, the search-coil method will usually provide a satisfactory and suitable alternative. It gives the mean resistivity over a wide area expeditiously, and with self-contained portable apparatus, but demands a wide range of frequency and separation for accuracy.

(C) The 4-electrode method is the only one possible where there are no lines. It gives greater geophysical detail than is necessary for interference calculations, so that care must be given to the deduction of the appropriate mean resistivity. The 4-electrode test is the simplest of the three to operate; it requires only portable apparatus and no auxiliary facilities. The method can be advised for all sites, with the possible reservation of those where experimental difficulties are accentuated by very high earth conductivity.

(D) Often it will be found that sufficient information as to the resistivity may be deduced from the geological structure.

Methods of measuring earth resistivity were discussed at a Plenary Meeting of the C.M.I. held in Paris in July, 1932, and recommendations very similar to the above were made.

TABLE 10.

Resistivity	Induction in μH per km at 50 cycles per sec. for a separation of:—			Induction in μH per km at 800 cycles per sec. for a separation of:—		
	10 metres	100 metres	1 000 metres	10 metres	100 metres	1 000 metres
ohm cm						
500	627	205	5	365	36	0·3
1 000	692	262	10	429	65	0·6
2 000	760	324	22	494	104	1·3
5 000	850	408	55	581	168	3
10 000	920	474	91	670	265	8
20 000	990	538	134	714	281	13·5
50 000	1 080	627	205	800	365	36
100 000	1 150	692	262	870	429	65
200 000	1 200	760	324	940	494	104

* See Bibliography, (9) and (10).

* The new low-range earth-tester (0–0·3 ohm) is not included in these remarks, which refer to the type with a minimum range of 0–3 ohms.

(ii) *Required Accuracy.*—Table 10 shows the variation of the coefficient of mutual induction with earth resistivity for inducing currents at 50 and 800 cycles per sec., and three typical separations between the lines. At separations less than 10 metres the mutual inductance becomes very nearly independent of the resistivity.

It will be seen that, except when the induction is small owing to a combination of wide separation with low earth-resistivity, it does not change greatly for a wide change in value of the earth resistivity. This is particularly true at 50 cycles per sec., so that, especially for the important case of induction from fault currents, a fairly wide range of error in the determination of the resistivity can be tolerated.

(4) Direct Induction.

(a) Magnetic Induction.

By direct induction is understood induction from the primary electromagnetic field due to the current in the power conductor, and in a zone immediately around the conductor where the secondary field, owing to the induced currents in the earth, is negligible by comparison.

Direct induction from balanced currents in the power system takes place on account of the fact that the couplings between a nearby communication conductor and individual power conductors of a group may not be equal. Values may be worked out from the geometry of the configuration.*

Induction from residual currents when the separation between the two circuits is small, is a special case of induction from earth currents generally. Earth conductivity does not greatly affect the result, but the heights of the power and telephone circuits have to be taken into account. The requisite formulæ are available.† Values of the mutual inductance varying from 1 770 μH per km at $16\frac{2}{3}$ cycles per sec. to 1 300 μH per km at 2 000 cycles per sec. were measured at Skillingaryd between two lines vertically below one another on the same poles, the separation being 1 metre. Slightly lower figures were obtained in Germany for the same configuration. These values are appropriate where supply companies maintain private telephone circuits on the same poles as the power conductors.

Measurement has been made by the authors of the induced longitudinal voltage in a pilot cable laid in the same trench as two 33-kV 3-core armoured power cables, and the values obtained are given in Table 11.

These tests were made with small currents and with the sheaths of all cables bonded to the earth-plate systems at the terminating substations. Later tests were made with 50-cycle currents up to 250 amperes in one core of the cable. With the same conditions the longitudinal voltage was equal to 98·5 mV per ampere, but was increased three times due to end effects when the power-cable sheaths were isolated at the ends. The results indicate that considerable voltages to earth may be induced in pilot cables during short-circuits. In normal operation serious interference is not to be anticipated, unless the harmonics are large or the route long.

A very thorough investigation has been made of the problems involved in laying a system of three unarmoured single-conductor cables, and rules have been laid down which minimize interference with a communication cable either close by or in the same trench.*

TABLE 11.

Frequency, cycles per sec.	2 000	1 600	1 200	800	600	500	350	175	100	30
Induced e.m.f., in millivolts per ampere in power cable, for 4·7 km	25	33	38	48	55	59	66	75	82	109

(b) Electric Induction.

Formulæ, depending only on classical and well-proven theorems in electrostatics, are available† for calculation of the electric induction except when the two lines cross, or are oblique to one another at a large angle. Experiments dealing with the latter case are envisaged by the C.M.I. Although of considerable interest, this problem cannot be regarded as one of prior importance in this country. Without exception Post Office lines are placed underground at all crossings with 132-kV lines. The same is done at crossings with overhead high-voltage lines of lower voltage, except when the consequent impairment of the telephone transmission renders this course undesirable. In the latter case, guards are installed between the two circuits, of such construction as to make contact between them virtually impossible. These requirements do not depend on electrostatic induction, and therefore no great financial saving is likely to result from research.

(5) Conclusions.

(a) Disturbance.

Experiment has decided the relative loss caused by disturbing currents of different frequencies in the telephone line, although their additive law in the case of a complex noise is not certain. A simple quadratic law has been taken provisionally, so that any noise disturbance may be expressed in terms of an equivalent e.m.f. at 800 cycles per sec. This may either be calculated or measured directly by apparatus already developed. In the same way consideration of their disturbing effects gives rise to the definition of a telephone interference factor for electrical machines, as the equivalent disturbing e.m.f., or current, at 800 cycles per sec. expressed as a percentage of the total output. Modern equipment can usually be kept within a T.I.F.

* See, for example, the report of the Californian Railroad Commission, on "Inductive Interference." † See Bibliography, (1) and (2).

* See Bibliography, (22). † *Ibid.*, (1).

of 0·5 or 1 per cent by suitable design or the use of auxiliary apparatus.

Disturbance from a.c. systems is usually due to earth currents, particularly multiples of the 3rd harmonic. Earthing the neutral may increase or decrease the earth currents, but a system with every neutral directly earthed does not necessarily give large neutral currents: in the most important case tested such a system gave, in fact, small currents. On cable systems, resonance may magnify the disturbance due to a particular harmonic.

If the earth current is known, the Carson–Pollaczek theory—the validity of which has been established by field measurements—may be applied to calculate the induced e.m.f.'s in any neighbouring communication circuit. Allowance must, however, be made for screening due to the presence of an earth wire or cable sheaths. Formulæ for the screening factor λ are given in this paper. The value of λ varies from 0·65 to 0·95 for earth wires. For cable sheaths, λ decreases rapidly with frequency, so that, when either the power or the communication circuit is contained in a cable, disturbance is greatly reduced. In telephone circuits the actual noise is a function of the unbalance of the circuit: the exact relationship still remains to be determined statistically.

The application of theory demands a knowledge of the local resistivity of the earth. This may be found by induction tests with actual or model circuits, but may also be measured more cheaply and easily by the search-coil method, when a source of earth currents already exists, or by a 4-electrode resistivity survey where no existing facilities are available.

The same principles apply to induction from traction systems, except that all the currents are residuals. The rails give a screening effect depending on the construction and bonding. In Great Britain, λ will lie between 0·2 and 0·4 for double-track railways, but will be greater for tramways. The main cases of interference arise from mercury-arc rectifiers, which give large 6th, 12th, 18th, and 24th harmonics. These may be satisfactorily suppressed by the use of resonant filter circuits across the output.

(*b*) *Danger.*

Danger arises from induction due to large transitory earth currents during short-circuits. The shortness of duration will, at least, not increase the induction to an important extent, and the Carson–Pollaczek theory may be used with screening effects allowed for as already described. In the case of earth wires, power-cable sheaths, unarmoured telephone cables, and well-bonded rails, the screening effect is not materially altered by the intensity of the current. Circuits run along a railway track are shielded to some extent from induction from an outside source.

The risk is that of electric and acoustic shock. The latter only may be alleviated in part by the use of protective devices.

(*c*) *Avoidance of Interference.*

Indications have been given in this paper as to how various types of interference may be decreased, as by the suitable choice of generators and transformers, neutral impedances and filters, output filters, additional earth wires, the use of power cables or telephone cables instead of overhead circuits, the design of cable sheaths, balancing of communication circuits, the choice of earthing methods, etc. The decision as to the appropriate method rests upon many considerations of cost, practicability, and convenience, which are outside the scope of this paper and must be determined by agreement for specific cases. Information will be found in this paper as to how the interference may be predetermined for given systems so that the merits of the various possible alternatives can be quantitatively compared, while, at the same time, the possibility of interference in connection with a projected system can be found beforehand.

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APPENDIX 1.

FORMULÆ FOR THE COMPENSATING EFFECTS OF CONDUCTORS IN PARALLEL WITH THE EARTH.

(a) General.

The mutual induction where an auxiliary conductor is in parallel with the earth is less than with a simple earth return, and can be obtained from the induction in the latter case by multiplying by a screening factor λ given by

$$\lambda = (Z_1 - M_1)/(Z + Z_1) \quad . \quad . \quad . \quad (19)$$

To a first approximation, Z is the impedance of the earth path and is given approximately by

$$Z = \left[\pi^2 f + j\omega\left(1 + 2\log_e\frac{2}{\gamma K h}\right)\right]10^{-4}\,\text{ohms per km} \; . \; (20)$$

where $K = 2\pi\sqrt{(f/\rho)}$; $\gamma = 1\cdot7811$; f = frequency; h = height of fault conductor in cm; $\omega = 2\pi f$; and ρ = resistivity of earth in C.G.S. units.

When applied to buried cables the formula requires modification, but a sufficient approximation is to take h as about 6 in. for cables buried direct in the ground, or as $\sqrt{2}$ times the radius of the duct for cables in multi-way ducts. The values of Z_1 and M_1 are given for the separate cases.

(b) Earth Wires.

$$Z_1 = \left[R_1 + j\omega\left\{A_1 + 2\log_e(h_1/r_1)\right\}\right]10^{-4}\,\text{ohms per km} \; . \; (21)$$

where R_1 = resistance of earth wire in absolute ohms per cm; h_1 = height of earth wire in cm; r_1 = radius of earth wire in cm; and A_1 = internal inductance (in absolute units per cm).

The value of A_1 depends on the stranding and the presence of a steel core, but it is normally about $0\cdot5$. Also

$$M_1 = 2j\omega\log_e(h_1/S_1)\,10^{-4}\,\text{ohms per km} \quad . \quad (22)$$

where S_1 = distance between the earth wire and the fault conductor, or the centre of gravity of the phase conductors for zero-phase currents.

(c) Rails in Overhead Traction Systems.

In this case M_1 is negligible, and we may put

$$nZ_1 = R + j\omega(A_1 + L_1)\,\text{ohms per km} \quad . \quad (23)$$

R is the resistance of the rails: it is made up of the ohmic resistance, which at higher frequencies is not so greatly affected by joints and is of the order of $0\cdot05$ ohm per km for British rails, and the skin-effect resistance, which increases with frequency—becoming about twice the ohmic resistance at 50 cycles per sec. and increasing at a more rapid rate subsequently. The value of Z_1 is, however, mainly determined by the inductance. This is composed of the internal inductance A_1, which is of the order of 1 000 μH per km, and the external inductance L_1, of about 250 μH per km. The internal inductance varies to some extent with frequency, and both this and the resistance should be found by measurement for accurate calculation. n is the number of rails, or twice the number of tracks.

(d) Cable Sheaths.

(i) *Unarmoured Cables.*—For one single-core or 3-core cable

$$Z_1 = \left[R_1 + 2j\omega\log_e(h/r)\right]10^{-4}\,\text{ohms per km} \; . \; (24)$$

$$Z_1 - M_1 = (R_1 + j\omega L_1)10^{-4}\,\text{ohms per km} \quad . \quad . \quad . \quad (25)$$

where R_1 = sheath resistance in absolute ohms per cm; r = radius of sheath (cm); and L_1 = internal inductance of sheath (absolute units per cm). The value of L_1 is usually small and is best obtained by measuring the e.m.f. between the sheath and a conductor very close to it, when a current is passed through the core.

For three single-core cables (flat spacing)

$$Z_1 = \left[R_1 + \tfrac{2}{3}j\omega\log_e\frac{h^3}{2rS^2}\right]10^{-4}\,\text{ohms per km} \quad . \quad (26)$$

$$M_1 = 2j\omega\log_e(h/S)\,10^{-4}\,\text{ohms per km} \quad . \quad . \quad . \quad (27)$$

where S = spacing between cables (cm).

These formulæ apply to transformer and plain cross bonding; with reactor bonding (jT_0/l) must be added to Z_1, where T_0 is the zero-phase reactance of the reactor in ohms, and l is the distance between bonds in km. In

addition, with cross bonding a current i is induced in the sheath and earth circuit, where

$$i/I = -2\omega j \log_e (h^3/2rS^2)/[R_1 + L_1 + M_1 - Z - 0 \cdot 92\omega j]$$

where I is the fault current, and $L_1 = 2j\omega \log_e (h/r) 10^{-4}$ ohms per km.

This correction is not usually important and depends on the resistance of the earth bonds, here assumed negligible. The sign indicates that this current is opposite to the normal earth current.

Where two cables or systems of cables have sheaths bonded together, the earth current is sometimes reduced still further by circulating currents induced round the sheaths and earth, apart from the effect of the addition of another conductor in parallel with the earth.

(ii) *Armoured Cables.*—The only case of practical interest is that of armoured 3-core cables, to which the following equations apply.

$$Z_1 = [R_1 + j\omega\{L_1' + 2 \log_e (h/r)\}] 10^{-4} \text{ ohms per km} \quad . (28)$$

$$Z_1 - M_1 = (R_1 + j\omega L_1) \ 10^{-4} \text{ ohms per km} \quad . (29)$$

The internal inductances L_1' and L_1 are slightly different, but may usually be taken as the same—depending on the proportion of current in the armour relative to the sheath. No exact formulæ can be given since sufficient measurements have not been made. R_1 now increases linearly with frequency owing to hysteresis and eddy losses in the iron, but usually this increase is not very great, although it depends on the type of cable and armour. L_1 varies very considerably with the type of cable and armour, and also with the lay of the armour. Its value is less with a long lay. In fact, with a long lay, R_1 is usually more important than the inductance over most of the frequency range. It is best to measure R_1 and L_1 if accuracy is desired, and it is hoped that this may form the subject of further work.

APPENDIX 2.

End Effects.

The theory of end effects with earth wires has already been given;* with rails, end effects are not of much importance if the tracks are constructed according to British practice.

If the sheath of a cable is insulated from earth at each end, the earth current flows into the sheath along the run, and is given approximately by

$$\lambda = \lambda_0 + (1 - \lambda_0) (\cosh ax/\cosh al) \quad . \quad . (30)$$

where λ = screening factor at x km from centre of run; λ_0 = screening factor with end effects neglected; $2l$ = length of run in km; $a^2 = G(Z + Z_1)$; G = leakage of sheath to earth, in ohms^{-1} per km; and Z and Z_1 have the meanings assigned to them in Appendix 1.

If the sheath is earthed at each end, the end effect is usually small except with impedance bonding, or where the fault is to the sheath of a cable in a duct. An expression similar to the previous one holds, namely

$$\lambda = \lambda_0 - [(1 - \lambda_0) (Z_1/Z) \cosh ax/(\cosh al + aL \sinh al)] \quad . (31)$$

For a single cable the term $aL \sinh al$ may be neglected, and the symbols are the same as before. For transformer bonding with three cables, Z_1 has one-third the value given in equation (26). Also

$$a^2 = \frac{Z_1 + Z}{(3R + T_0)/L}$$

where L = length between bonds; T_0 = zero-phase impedance of bonding transformer; and R = resistance of earth connection at bonds.

For plain cross bonding, T_0 is zero. Equation (31) holds for reactor bonding, except that

$$a^2 = \frac{Z_1 + Z + (T_0/L)}{RL}$$

T_0 being the impedance of the reactor inserted at the bonds.

These infinitesimal solutions are satisfactory for deducing the general nature of such effects, but the precise calculation requires a solution by means of repeated networks where bonding devices and earth plates are used. Since end calculations are of importance from the point of view of operation characteristics, they are not given here but may be found in various other E.R.A. reports.

* P. D. Morgan and S. Whitehead: *loc. cit.*

Discussion before The Institution, 23rd November, 1933.

Mr. S. C. Bartholomew: This paper is a splendid example of co-operation, both national and international. It gives the result of work done by a league of nations composed of engineers, and, as would be expected, something tangible has resulted. I should like to give some details of the work of the C.C.I. and the C.M.I., to which the authors referred in presenting the paper. The former body, which was set up about 1924 to develop long-distance telephony, has formulated certain guiding principles, called "Directives," dealing with the subject of power circuit interference. In drawing up these Directives the C.C.I. received assistance from various international power bodies, who drew attention to certain questions which could only be settled by practical tests, and the C.M.I. was set up as a result of the discussions which arose. This Commission is composed not only of representatives of the telephone and telegraph administrations of the world, but also of international bodies representing the railways, the tramways, the electric light and power distributors, and various big manufacturing companies interested in communications. The Institution and the Electrical Research Association are both represented on the C.M.I. In 1924, when the last paper on this subject of interference* was read before the Institution, the main question was that of noise disturbance; up to that time the possibilities of danger, although realized to some extent, had not appeared to

* S. C. Bartholomew: *Journal I.E.E.*, 1924, vol. 62, p. 817.

be very real. In 1925, however, a paper* was read at the Paris E.H.T. Conference dealing with experiences on the Midi Railway and mentioning a large number of cases of acoustic shock and injury to telephone operators by electric shock; in fact, electrocution is referred to. With regard to noise measurement, it would perhaps be interesting to point out why there has been a change from a subjective method to an objective method. Before the development of a noise-measuring set by the British Post Office, two methods were available—one American and the other German—in which the comparison was made in one case with the noise produced by a buzzer and in the other with a note having a frequency of 800 cycles per sec. At a meeting of the C.M.I. at the Post Office Research Station, Dollis Hill, it was clearly proved that the subjective method gave such varied results according to different observers that a better method was needed, and the C.C.I. and C.M.I. accordingly agreed that an objective method should be developed on the lines of the Post Office suggestion. In the first tests of the German, American, and British apparatus, the British was proved to be the best of the three, its results being in closer agreement with what could be expected from theoretical considerations. Returning to the question of danger, I think some stress should be laid on the difficult position in this country. The Electricity Commissioners have definitely laid it down that the neutral points of all systems shall be earthed. This is not the general practice throughout the world. Earthing the neutral points, and more particularly direct earthing, introduces the possibility of danger from electric shock and damage to plant, whilst on the other hand the unearthed neutral is more likely to give trouble from acoustic shock. A report of an American Committee (Joint Committee of National Electric Light Association and Bell Telephone Systems) which is run on practically the same lines as the E.R.A. emphasizes the difficulties and dangers which must be faced when solidly-earthed-neutral power systems run in proximity to communication circuits. These effects are analysed in a symposium which was presented to the Winter Convention of the American Institute of Electrical Engineers in January, 1931.† It is not necessary to give fully the possibilities referred to in the reports of service interruption, false signals, damage to central-office or other telephone plant, and acoustic shock; perhaps the following extract referring to electric shock will suffice. "Telephone linemen in the course of their work upon wires at relatively close spacing, cannot avoid getting in contact with the wires and if the wires were subject to sufficient induced voltage, the men would be liable to receive electric shocks. On severely exposed lines such voltages are liable to occur at any time, suddenly and without warning. Electric shock might either injure a lineman directly or startle him and cause him to lose his hold and fall from the pole. Voltage to ground due to induction appears not only within the exposed section of line but considerably beyond. A similar, and in some respects, worse, condition may exist with respect to employees working on cable circuits which are either exposed or directly connected to exposed circuits. In cables the wires on which the foreign voltage appears are very close to the grounded metal sheath and usually also to other wires at approximately earth potential, as well as to the earth itself. This problem has become more difficult with the rapid growth of the telephone and electric power systems and is engaging the Sub-Committee's serious attention." This passage shows that the possibility of trouble from direct earthing is a very real one. In connection with the calculation of the magnitude of interference effects some credit should be given to such early workers as Mayr, Breisig, Rudenberg, and others, although their formulæ ultimately proved to be inaccurate. The Japanese also developed empirical formulæ which they claimed were applicable to the interference problems encountered in their own country; but they have since adopted, as we have in Europe, the formula of Pollaczek and Carson. Turning to the question of earth resistance, I can recall a Swedish engineer stating many years ago that the separating distance between a power line and a telephone line did not materially affect the degree of interference; the only important factor to be taken into consideration being the length of parallelism. In the end this was proved to be due to the very high resistivity of the soil in Sweden, which amounts to over 200 000 ohm-cm. On the other hand, in this country the Central Electricity Board would not accept in the first instance the formula of Rudenberg or the earth resistivity of 20 000 ohm-cm allowed for in that formula. They very rightly wanted this figure checked, and very artfully, as it seems to me, they chose that the first tests should be made at Runcorn, where the land is marshy and near the Manchester Ship Canal. Instead of 20 000 ohm-cm, the value obtained was about 1 000 ohm-cm. The Board also showed a good deal of foresight in investigating the shielding effect of the earth wire on the power line supports. It was Mr. Beard, I think, who asked if the Post Office could not make some allowance for this, and in the end it was proved that the earth wire put up by the Board reduced the trouble by roughly $33\frac{1}{3}$ per cent. With regard to mercury-arc rectifiers, there is a great difference in the inductive effects as between their use on the third-rail and the overhead contact-wire system. On the Southern Railway, where a third rail is used, the disturbance is moderate, but the same type of rectifier in the South of France, where overhead contact is used, is very troublesome, and shunts are essential. My own view is that shunts should always be fitted. There is one contradiction in the paper to which I should like to call attention. On page 220 the authors say that the effect of the railway track is to reduce the disturbance, but on page 217 they point out that on the L.M.S. line to Carlisle the disturbance was increased.

Dr. A. Russell: I am pleased to see that the authors use Pollaczek's formula No. 1. I remember some 50 years ago being in Lord Kelvin's class at Glasgow University. He came in one afternoon in a state of great elation, and said he had invented two new functions, which he proposed to call the *ber* and *bei* functions. He said they were just as simple as the cosine and sine functions, and could be calculated in the same way from series. He showed how they could be applied to the

* P. Boyé: Report of the International Conference on Large Electric Systems, 1925, vol. 2, p. 93.

† *Transactions of the American I.E.E.*, 1931, vol. 50, p. 437.

problem of the transmission of heat along a cylinder, and got out solutions in terms of them. In 1889, in his presidential address* to the Institution, he defined these functions fully and gave tables of them which had been computed by Prof. Magnus Maclean. Some 13 years after that, when I was solving the problem of the skin effect in concentric mains, I saw that the solution could be simplified by introducing two new functions, which I called the *ker* and the *kei* functions, imitating Kelvin. His names of *ber* and *bei* stood for "Bessel real" and "Bessel imaginary," and I therefore thought "Kelvin real" and "Kelvin imaginary" would do just as well for these other functions. Their differential coefficients are used in Pollaczek's formula No. 1. The British Association have computed tables of these formulæ and their differential coefficients, and they are now used internationally.

Mr. J. A. Broughall: I should like to deal with the question of whether filter circuits are essential when mercury-arc rectifiers are used for conversion in traction substations. The rectifier described in the paper was one of the first of its kind used in traction service in this country, and the filter circuits were installed to avoid the possibility of telephone interference; but the experiment of running with the filter circuits disconnected was not prolonged for a sufficient length of time to demonstrate that these circuits were essential. In the case of rectifier substations which we have on other lines, however, where the third- and fourth-conductor rail system is used, we have shown over a period of 18 months that telephone circuits can be operated without any interference. This is what one would expect, having regard to the greater separation between the conductor rails and the telephone circuits, and probably also to the opposing effect of the current in the third and fourth rails. Equally, on the other electrified lines where the substation plant is of the glass-bulb rectifier type with 12-phase connection, we have not found any interference without filter circuits. In these cases we have only a third rail with return by the running rails, and the current is transmitted to the substations by overhead conductors, paralleling the track, where one might possibly have anticipated distortion of the a.c. wave-form by the rectifier.

Mr. C. W. Marshall: With regard to interference in normal operation, I think it should be recorded that with 3 400 miles of 132-kV down to 33-kV lines in operation, there has been no interference with communication circuits of modern design for the period of operation, which extends to over 4 years. Regarding interference in transitory states, I think it should be recognized that the presence of power lines, suitably located, does not add materially to the dangers to which communication lines are subjected. In this paper there are about a dozen references to danger, and that makes one feel that there may have been some neglect in providing against the dangers which exist, quite apart from those due to power circuits. I should be interested to learn what safeguards are adopted by the Post Office to protect linemen from distant lightning storms and operators from acoustic shock arising from lightning or the high potentials emanating from their own apparatus. Reference has been made to the C.C.I. Directives and to the endeavours which are made to reduce exposures so that the figure of 300 volts is not exceeded. These "Directives" are, as Mr. Bartholomew pointed out, merely guiding principles; they are based largely on Continental experience, and it should be remembered that Continental power systems use protective equipments which are relatively slow in operation, with clearing periods of the order of 4 or 5 seconds. I feel that rapid clearance of faults is the most economical and satisfactory way of dealing with anticipated trouble. As regards protective devices, I think the authors might have made some reference to mercury-arc protectors, which have a low discharge voltage, a high current capacity, and good self-restoring properties. Reference is made to the tests at Portobello, which proved that multiple earthing did not give rise to high earth currents and satisfied even the Post Office engineers that there was little to be feared. They were inclined (but quite unjustly) to attribute that particular success to good choice of test position. With regard to the calculation of interference effects, I think it would be extremely advantageous to introduce methods employed in America, whereby mutual impedances are used in preference to mutual inductances. In this connection special tribute should be paid to Dr. Klewe, of the German Reichspost, who has been extremely helpful in putting his experience, knowledge, and apparatus, at the disposal of those interested. A good deal of prominence has been given to the Carlisle–Lancaster exposure, which seems to be regarded as an extremely severe one. This is not the case. For example, I can quote an instance of a line in Japan which is 282 km in length and has only a 404-metre separation distance where there is an induced voltage of 29·1 volts per ampere, as against 2·45 in the British case. With reference to screening, the tests made by the Central Board in conjunction with the railway companies have shown that the presence of the rails reduces the induced voltage in their adjacent communication lines by at least 70 per cent. Finally, I think that in the Bibliography reference should be made to a paper by Mr. Jackman,* of the Post Office, which puts the essential facts relating to inductive interference and fault currents on high-tension power lines in a very clear and interesting way.

Colonel H. Carter: Since, as a member of the E.R.A. committee which controlled the researches dealt with in the paper, I have already had ample opportunity to consider the matter dealt with, I propose to confine my remarks mainly to the subject of co-operation between the telephone and power-supply sections of the industry in the solution of problems of this kind. The heavy- and light-current sides of the industry are becoming more and more interdependent. It is, of course, of immense importance to the Post Office to have a cheap, reliable, and easily available supply of power, while on the other hand the Central Electricity Board have made considerable use of Post Office lines for control purposes. Anything that can be done, therefore, to find a solution of problems where the interests of the two sides clash is all to the good. Many problems arise in this connection which call for fairly elaborate researches, and for these

* E E 1889, vol. 18, p. 4.

* *Post Office Electrical Engineers' Journal*, 1933, vol. 26, p. 97.

extensive facilities are necessary both on the communications side and on the power side. It is very desirable that the problem should be considered by the best available experts from both sides, and it was therefore a great step forward to get it dealt with by a body such as the Electrical Research Association, rather than to treat individual problems as they arise, with the individual undertaker concerned. Much still remains to be done, however, in finding satisfactory technical solutions for the proved difficulties. With regard to the paper itself, I cannot help regretting that it has been necessary to condense it so severely. It would have been a great advantage if it could have contained a complete record of the telephone interference investigations of the last three years. The question of the effect of earth resistance has always been a very interesting one to me, and although these investigations have shown that the problem is more difficult than was at first supposed they have at the same time demonstrated that there are reasonably cheap and easy experimental methods available for solving it in any individual case. The production of a resistivity map, if it gives sufficient detail, will enable calculations to be made with some accuracy. In conclusion, I should like to pay a tribute to those members of the staff of the Post Office Research Section who have produced a noise-measuring set which is internationally acknowledged to be the best of its kind so far.

Mr. A. Broughton Edge: The few remarks I have to make refer to the earth-resistivity map which has been shown by the authors. I believe it to be the first of its kind, and it originated in the following way. At the conclusion of the work of the Imperial Geophysical Survey in Australia, where a large number of earth-resistivity measurements were made, I suggested to the Department of Scientific and Industrial Research that it would be a relatively easy matter to prepare a map showing the major variations of earth resistivity in this country. As a result I was referred to the E.R.A., whose Sub-Committee on Inductive Interference gave me the very interesting task of preparing such a map of England, Wales, and South Scotland. The preparation of this map has been based upon the well-established fact that the earth-resistivity variations in any area depend almost entirely upon geological factors, or, to be more precise, on the lithological character of the various rock formations which exist there. In a country such as this, where very detailed geological information is available, there is no serious difficulty in producing an earth-resistivity map to any reasonable scale. In this particular case a scale of 10 miles to the inch was specified, but the map could have been prepared on a scale of 4 miles to the inch, or even 1 mile to the inch, if circumstances had made it necessary; although of course the larger the scale the more numerous must be the field measurements and the more detailed the search amongst the geological records. The general procedure which I adopted was to obtain, by actual measurement, representative values of the resistivity of what geologists call the "solid" formations—that is to say, the foundation rocks of the country, such as the carboniferous limestone, coal measures, chalk, London clay, and so on—and also a further series of values for the superficial deposits, such as gravels, sands, and clays, which overlie the solid rocks. From such data and from existing geological records it is possible to compute the resistivity for almost any part of the country, certainly with the degree of accuracy required by the map I was asked to undertake. Although of a provisional character only, the map shown by the authors indicates quite clearly that high-resistivity conditions prevail amongst the older rocks of the North and West of England, whereas relatively low values are common to most of the industrial areas of the Midlands and in the southern and south-eastern portions of the country.

Mr. G. C. Marris: The very interesting discussion which we have had on earth resistance prompts me to record a measurement made in the coal measures of Derbyshire, some miles south of Chesterfield. An opportunity occurred to put down 200 yards of wire 20 yards from a power line, and the voltage measured on that occasion was consistent with an earth resistivity of about 1 500 ohm-cm. With regard to the general question of danger, I should like to ask the authors about dangerous or appreciable voltages arising from high-frequency surges caused by switching and lightning disturbances. Various publications in the last few years have indicated that switching may set up over-voltages of 2 or 3 times the flash-over voltage of the line, resulting in the development of standing or travelling waves with currents limited by the surge impedance of the line, and so of magnitude comparable with the short-circuit current. The frequency will depend on the length of the line, and in one case 12 half-cycles of 2 000-cycle current were recorded. There is reason to think that the net effective exposure in kilometre-amperes is usually not great, but it would be interesting to know whether dangerous induced voltages have been recorded from such a cause. I can find no reference to them in any of the C.C.I. publications on the subject. The voltages would appear to be serious, because although the mutual inductance decreases with frequency, the mutual impedance increases more rapidly. On page 211 the authors state: "The most harmful type of fault from the point of view of interference is usually when one phase is earthed." Is this a safe generalization to make, even with the word "usually" inserted? I ask this question because it appears that simultaneous faults, widely separated in space, do in fact occur, and that these double earth-faults give currents the magnitude of which may be 10 times that of those calculated from the short-circuit current, taking into account the resistances in the neutral in the case of the earthed-neutral system. A discussion of some such double earth-faults was recently given by Wild.*

Captain A. C. Timmis: It may be of interest to mention briefly the elaborate series of tests which is being carried out in Paris at the present time under the auspices of the C.C.I. for determining the harmful effect of interference voltages on the intelligibility of telephone signals, a question which arises whenever an interference problem comes under review. As the authors have shown, the power engineer may calculate the voltage of interference which is likely to get on to the

* *Wissenschaftliche Veröffentlichungen aus dem Siemens-Konzern*, 1931, vol. 10, p. 51.

telephone line, and, having done that, he naturally asks the telephone engineer how much of it he can stand. The telephone engineer obtains his answer to this question by setting up on a telephone circuit artificial conditions representing a reasonably good trunk call, estimating the harmful effect of the noise on the telephone speech by determining the percentage of meaningless words which can be correctly received over the circuit. In the C.C.I. experiments, which are partly completed, an artificial line and artificially-produced room noise at the receiving end from a gramophone record were used. The speech level at the sending end was carefully kept constant, and various noises—single frequencies ranging from 150 to 1 450 cycles per sec.—were put on to represent power-circuit interference; in addition, two or three mixtures of frequencies (particularly of 450, 800, and 1 450 cycles per sec.) were put on to represent an accidental mixture, in contrast to the mixture of 300, 600, 900, and 1 200 cycles per sec., stated to be a musical combination, which is obtained from a hexaphase rectifier. It was found that the musical noise produced just about the same effect on intelligibility as did the haphazard mixture of 450, 800, and 1 450 cycles per sec. At one level of received speech the amount of noise which produces the figure suggested by the C.C.I. as reasonable (5 per cent reduction of articulation) has already been determined. The impairment of the speech caused by the noise depends on the ratio of the two currents. Unfortunately, it is almost impossible to determine this ratio when one current is speech of an extremely peaky nature and the other is a steady alternating current from the power induction. Certain fairly definite results have, however, been obtained, and the next step in the experiments is to use a lower level of telephone speech and to measure the effect, no doubt more severe, at that level. It is interesting to note that in America the most friendly relations have been established between telephone engineers and power engineers; in fact, the former have actually persuaded the latter to understand their rather elaborate system of expressing the impairment on a telephone line as so many decibels of attenuation added to that line. I do not see why we in Europe, in spite of our differences of nationality, should not work together in the same friendly manner.

Mr. R. O. Kapp: Up to the time when the investigations were made which have been described to us in the paper, all the work on this subject had been done by research workers of other countries—California, Germany, and Sweden. It is therefore a matter for some national pride that the work of the present authors shows a considerable advance on anything that had been done before. Those who are not specialists in the subject dealt with in the paper, and particularly those who are power engineers, find it difficult to understand interference effects. I do not think it would be impossible, if attention were given to the problem of exposition as well as to that of investigation, to present the material collected by the workers engaged in this type of research in such a way that its implications could be grasped by power engineers. The general impression which one might get from the paper and from the discussion which has raged on the subject for some years is that power lines are noisy disturbers of the peace, and that they have to be put in the dock and charged with their offences. If this were done, two lines of argument would be possible. On the one hand, it might be held that power circuits cause malicious damage, and at the other extreme they might be regarded as acts of God. The extent to which power lines operate in the same way as acts of God is a matter of interest, and I should like to ask whether any statistics are available of the number of disturbances in this and other countries due to short-circuits on power lines, and the number of disturbances due to lightning. Even if we cannot say that power lines are acts of God, we can at least assert that power engineers are only an insignificant ally, and from this I would draw the conclusion that one of the important steps to be taken by Post Office engineers is to guard themselves against power lines just as they have to guard themselves against lightning. The development, therefore, of appliances which have for their object protection against lightning and incidentally against power circuits, is one of the most important lines of future progress in connection with this subject.

Mr. P. B. Frost: Fig. 9 shows a striking difference in the mutual inductance between two parallel lines earthed at both ends for earth resistivities of 220 000 and 4 700 ohm-cm respectively. At a separation of 100 metres the mutual inductance for a resistivity of 220 000 ohm-cm is just twice as great as the mutual inductance for the same separation and a soil whose resistivity is 4 700 ohm-cm, but at the greater separation of 1 000 metres the mutual inductance for the high resistivity of 220 000 ohm-cm is no less than 6 times that for the low resistivity of 4 700 ohm-cm. Hitherto practically all the calculations which have been made of the induced voltage with a view to estimating the safe fault current have been based on an earth resistivity of 4 700 ohm-cm, which was recommended, in default of more certain knowledge, by the C.C.I. I am afraid we shall find, however, from a study of the map produced by Mr. Broughton Edge, that in a great many parts of this country the resistivity is much higher than 4 700 ohm-cm and that the calculated values of the induced voltage have therefore been greatly under-estimated in some places. Is the "telephone interference factor," mentioned on page 203, the quantity which is defined by the C.C.I. as "telephone form factor"? The relative amounts of noise emitted from rectifiers, shown in Fig. 4, need some emphasizing, because the curves for rectifiers without filters are drawn to one-tenth the scale of those for rectifiers with filters; unless the diagram is studied carefully one may gather that the two are not very greatly different. The authors refer to the relative unimportance of tests made on lines for electrostatic effect; as it may happen that lines which have been considered dangerous from an electromagnetic point of view may be worked with an unearthed neutral (in which case the electrostatic effect would have to be calculated and allowed for), it is desirable that the purely theoretical data which we have at present should be confirmed by some simple practical tests. With the 132-kV lines we have arranged to cross underground at all points, but the exposure on either side, which extends from about 60 ft. up to about 360 ft. from the line, is

important and could lead to danger. I should be very glad if future experiments could be directed towards measuring the effect of electrostatic induction. With regard to the leading of telephone lines into power stations and the installing of telephone apparatus in such stations, all ordinary risk of contacts with dangerous voltages can be provided for quite easily, but to guard against the rise of earth-plate potential which can occur under fault conditions certain precautions are necessary both in leading-in and in installing apparatus. The risks are not great where the resistance to earth is small, and I think that for a great many grid stations the resistance of the earth system is so low as to make any special precautions unnecessary. On the other hand, there are a number of stations where the resistance is high and cannot be made any lower, and in these cases elaborate precautions are necessary, not only from the point of view of protecting apparatus and lines (and, of course, the general public through those lines), but also in order to safeguard the staff using the telephone in the station building. The Swiss Government have realized that risks are involved and have issued regulations for the introduction of communication circuits into power stations which are more stringent and more elaborate than those formulated by the British Post Office.

Mr. P. D. Morgan: On pages 211 and 212 the authors refer to the disturbing effects of neutral and residual currents during normal operation of a power system. At the present time there is an increasing demand for the multiple earthing of power systems, and a number of queries are arising regarding its effect on interference with communication circuits. It is sometimes assumed in such cases that the third harmonic and its multiples are the primary cause of disturbance, but recent investigations by the E.R.A. show that this is not necessarily the case. Tests were recently made on a 11-kV line system to compare the disturbance due to neutral currents when there was one earth on the system and when there were five. The results showed that the principal disturbance in this case arose not from third harmonics but from residual currents. With one earth on the system the disturbance was mainly due to a frequency of about 700 cycles per sec.; with five earths on the system the characteristic impedance was altered, and a frequency of about 1 200 cycles per sec. was primarily responsible. This change of characteristic impedance with the number of earthed points constitutes a serious problem, because it renders pre-calculation of the disturbing effects with multiple earths practically impossible in the present state of knowledge. I should therefore like to ask the authors what help they can give or what light they can throw on this question.

Mr. J. Urmston: The authors will no doubt be pleased to learn that the work which they and their collaborators have done has been turned to very practical use by my colleagues and myself in the design and construction of a telephone line having a parallelism with a power line of over 300 miles. The operating voltage of the power line was 132 kV for 200 miles and 60 kV for the remainder, and the distance separating the telephone line from the power line had to be between 150 and 300 ft. An application of the formula which had been obtained and confirmed by members of the E.R.A. and the C.M.I. showed that there should be no insurmountable difficulty in operating the telephone line under the conditions required. The line has been erected, and it can be considered highly satisfactory that the noise tests which have been taken indicate that the amount of interference is innocuous. It was particularly interesting to find that when the 132-kV line was deliberately short-circuited to earth at a point 180 miles away from the generating station the effect on the noise-testing set, which was being used for the purpose of recording the shock, was unnoticeable. Another test showed that the induced voltage on a 20-mile section of the telephone line on open circuit rose to 420 volts as indicated by an electrostatic voltmeter; this voltage dropped to 20 volts when a moving-coil instrument was used, but gradually rose again to 420 volts when this instrument was taken away and replaced by the electrostatic voltmeter. For this reason it has been suggested that the greater part of the induced voltage was due to electrostatic induction; I should be glad if the authors would express an opinion on the point. It would be very useful to line designers, particularly to those entrusted with the construction of long parallels such as the one I have mentioned, if the authors could suggest a reliable and easy method of testing the amount of noise during construction, and of determining the maximum amount of noise which could be allowed.

Mr. P. W. Blye (U.S.A.) (*communicated*): The paper discusses methods of measuring the telephone interference factor of power system voltages and the results obtained by these methods on various common types of power system machinery. It is interesting to compare European and American practice and experience in this field. As regards the method of measuring telephone interference factor (T.I.F.), the American practice is to express the T.I.F. in arbitrary units in terms of the transfer admittance of the weighting network used. There may be some advantage, from the point of view of making noise estimates and of visualizing the degree of wave distortion, in the authors' method of expressing the T.I.F. in terms of a single-frequency voltage having the same inductive effect as the complex wave in question. In Europe, where the noise meter is used in measuring power-system T.I.F., a frequency-weighting characteristic is employed which is based upon the interfering effects of single-frequency currents in the receiver of a telephone subscriber's set. In the case of the American noise meter this weighting characteristic is used only where measurements are actually made across a subscriber's receiver. A second network giving a so-called "line weighting" characteristic is used where the measurements are to be made at toll-circuit terminals. The latter network allows for the attenuation/frequency characteristic of the circuit and apparatus between the toll-circuit terminals and the subscriber's receiver. Since noise-frequency components induced from power circuits are usually subjected to all or a large part of this selective attenuation, American practice is to use the so-called "line weighting" network in measuring T.I.F. Another point which is of interest is the omission of the factor of proportionality with frequency from the weighting curve of the T.I.F. meter, justified by the authors on

the basis that power circuits are mainly reactive and that the inductive effects of currents are controlling. American practice is to cover cases of this type by rating the T.I.F. of the current as well as that of the voltage and to include in both the factor of proportionality with frequency. It should be understood, of course, that the use of such a factor is only an approximation as it assumes that the telephone-circuit unbalance, shielding effects, and the propagation of the noise currents from the exposure to the circuit terminals, are independent of frequency. Where the telephone circuits are in cable or when signalling apparatus is employed having unbalances which are not independent of frequency, these assumptions are not valid, so that for such situations the T.I.F. may not be of much significance. It probably has its greatest usefulness for exposures involving overhead power transmission lines and open-wire telephone circuits. With regard to the average wave-shape of a.c. systems, British and American experience seem to be in accord. The T.I.F. measured by the American method in the cases mentioned below has been converted to an equivalent 800-cycle voltage to permit direct comparison with the European figures. In an extensive survey of wave-shape conducted jointly by American power and telephone engineers, the average voltage T.I.F. of steam-turbine generators was found to be about 0·6 per cent. This is in line with the figures given in the present paper. In the case of water-driven machines the average was found to be 1·4 per cent. In all types of generators, as brought out by the authors, the tendency was toward lower T.I.F.'s on the larger machines. The results of the wave-shape survey indicated that on the average the voltage T.I.F. on a.c. transmission and distribution systems was approximately 0·5 per cent. The results of the survey also confirmed British experience as regards the wave-shape of the d.c. end of rotary convertors. The T.I.F. of 33 machines tested ranged from 0·15 per cent to 2·6 per cent, the average figure being 0·62 per cent. It is interesting to note in this connection that in two cases where the T.I.F. of rotary convertors was of the order of 2·5 per cent, a resonant shunt on the d.c. system was used in order to provide satisfactory co-ordination with exposed telephone circuits. The T.I.F.'s experienced with d.c. generators (600 volts) in this country are apparently considerably higher than those found in Europe. On 26 machines tested, the open-circuit T.I.F. was found to vary from 0·08 to 12 per cent, the average figure being 2·7 per cent. This compares with a maximum figure of 2·5 per cent given in the paper. The experience with d.c. systems supplied by mercury-arc rectifiers seems to be much the same in Europe as in America. It has been found practicable to co-ordinate d.c. traction circuits with exposed telephone lines when filtering apparatus is applied to the rectifier outputs. A more difficult problem is presented by the wave-shape distortion caused by the rectifier on the a.c. supply circuits, however, and considerable attention is now being given to this matter in this country. Some discussion of the problem is given in a recent paper entitled "Effects of Rectifiers on System Wave Shape."* From data given in the present paper it appears that similar problems involving telephone interference from triple harmonics arising in 3-phase generators directly connected to power systems and operating with earthed neutrals have been encountered in Europe and in America. This question was investigated by the Joint Sub-Committee on Development and Research of the National Electric Light Association and the Bell Telephone System: the results of the study are presented in Engineering Report No. 12 of that organization.

Mr. C. G. Carrothers (*communicated*): The authors refer on page 211 to the limitation of residual current by means of resistances or Petersen coils in the neutral earth connections of the transformers. Devices of this type have been applied successfully, but they have the disadvantage that the neutral voltage of the whole of the system is displaced under earth-fault conditions. This leads to interference due to residual voltage on the lines and exposes the insulation of the transformers and lines to abnormal stresses. In Fig. 12 it is shown that the zero phase-sequence network can be considered separately from the balanced network; it would be interesting to know whether the authors have contemplated the possibility of increasing the line impedances in the zero phase-sequence network without introducing an appreciable alteration in the corresponding impedances in the balanced network. This might be contrived by the use of chokes in the ends of lines coupled magnetically, so as to offer comparatively small impedance to load currents. If this could be done, the following important operating advantages would be obtained on a system of the type shown in Fig. 12. (1) The current to an earth fault would be restricted in amount. (2) Current and voltage residuals could be confined almost entirely to the earthed section of line. (3) The residual current would be supplied from each end of the earth section in equal parts, so that there would be a tendency for the induction on parallel circuits to cancel out. (4) The confinement of the disturbance to the affected section would make the selectivity of the line protective apparatus quite certain.

Dr. J. Collard (*communicated*): The authors have mentioned my method of measuring the earth resistivity by means of a search coil, and it may therefore be of interest to give some representative values obtained in England by this method. Table A (page 229) gives approximate values of the resistivity for various geological formations, and shows the very wide range of resistivity values met with in practice. I should like to modify the authors' statement that a wide range of frequency and separation is required by the search-coil method. It is quite possible to obtain good results with one frequency only, e.g. the 150-cycle component of a power system. With regard to the range of separations required, this depends on the resistivity. With a value of 200 ohm-cm separations from 10 to 100 metres are required, while for 100 000 ohm-cm separations up to 1 000 metres would be necessary. Throughout the paper the authors use the expression "telephone interference factor" (T.I.F.) as the equivalent disturbing voltage at 800 cycles per sec. expressed as a percentage of the total voltage. This expression was first used in America to define the relative interfering effect of a power-supply voltage, and was applied to the results

* P. W. Blye and H. E. Kent: *Electrical Engineering*, 1934, vol. 53, p. 54.

obtained by a T.I.F. meter incorporating the well-known Osborne weighting network. The results given by this instrument, however, were purely arbitrary, being expressed as the current in microamperes at the output of the weighting network divided by the voltage in volts across the input to the set. The values of T.I.F. given by the American apparatus, which have been extensively quoted in America, do not, therefore, agree with the values based on the authors' definition. There is thus a possibility of confusion, and it would be an advantage if a different name could be given to the quantity defined by the authors. In considering the question of induction in cable circuits the authors state that the induction in the cable can be obtained by multiplying by λ the corresponding e.m.f. for the open-wire case, where $\lambda = R_s/(R_s + j\omega L_s)$. It is worth while emphasizing that in the case of noise frequencies this statement

TABLE A.

Formation	Resistivity, ohm-cm
Alluvium	200–400
Clay	600–1 000
Coal-bearing measures	2 000–5 000
Chalk	4 000–5 000
Carboniferous limestone	5 000–6 000
Sandstone	6 000–10 000
Igneous rocks	50 000–100 000

only applies to the induced e.m.f., and not to the voltage to earth which actually produces the noise. The voltage to earth along a conductor subjected to uniform magnetic induction is given by the expression

$$v_x = \frac{E}{P(e^{Pl} - e^{-Pl})}\left[(1 - e^{Pl})e^{-Px} + (1 - e^{-Pl})e^{Px}\right]$$

where P is the propagation constant of the conductor with earth return, l the length of conductor, and E the induced voltage per unit length. In considering the relative susceptibility to noise of cable and open-wire circuits it is thus necessary to take into account this propagation effect. It is of interest to note that for values of P obtained for typical circuits this effect has the result of reducing the noise in the cable circuits relative to that in the corresponding open-wire case. This reduction is, of course, additional to the reduction due to the shielding effect of the cable sheath.

Mr. L. P. Ferris (U.S.A.) (*communicated*): I shall confine my comments to certain differences between European and American experiences and points of view. With respect to the risk from electric induction at crossings, our experience has not indicated that such risk is important and we have given very little study to the matter. Some approximate calculations which have been made since receipt of the paper support my belief that electric induction presents little or no electric shock hazard where an open-wire communication line crosses the route of a transmission line at right angles. Magnetic induction is, of course, zero for the case of perpendicular crossings, and possible contacts between the two lines do not come within the scope of the paper. In regard to the induced voltage in a communication line during the first few microseconds following the establishment of an earth fault, the complexity of the problem and the necessity for the simplifying assumptions made in the theoretical investigations of Ollendorf,* Peterson,† Riordan,‡ and Radley and Josephs,§ seem to leave the results open to some question as to the accuracy with which they represent actual conditions. I am inclined to agree, however, with Messrs. Radley and Josephs that the possible extra rise in voltage during this period is not cause for serious concern in exposures to a.c. power lines. From the point of view of electric shock, the transient voltage might exceed the steady-state value quite substantially without materially affecting the danger, provided its duration was only a few microseconds. In connection with the matter of induction from earth-return currents, I should like to refer to the paper by Bowen and Gilkeson‖ and to Engineering Report No. 14 of the Joint Development and Research Sub-Committee of the National Electric Light Association and the Bell Telephone System, where there are described the results of some experimental investigations conducted in the United States. These investigations were designed to test the theoretical formulæ for the mutual impedances of earth-return circuits and to develop simple methods for obtaining the information requisite to the calculation of the mutual impedances between power and telephone lines. In general, the magnitudes of observed mutual impedances have been in good agreement with those computed by the Carson formula, but in most cases the observed and computed phase angles have differed substantially. These differences were not due to proximity of the earth connections of the two circuits, for extreme precautions were taken to ensure that effects arising from such a cause would be negligible. We believe that the disagreement between observed and computed phase angles is due in most cases to stratification, or other lack of uniformity in the earth. In this connection we note that in the tests at Shap (E.R.A. Report Ref. M/T14)¶ the measured phase angles differed greatly from those calculated, the differences being much larger than any which have been observed in our work. In measurements at the higher frequencies, we have frequently found it necessary to correct our observations for the voltage drops through the resistances of the earth connections on the secondary lines owing to the charging currents of the capacitances between the measuring leads and between these and earth. Were such corrections applied in the reduction of the observed data at Shap? If not, this might largely account for the discrepancies in the phase angles. We have found it very advisable to use a measuring circuit which is "balanced" with respect to earth. A modified formula applying for an earth having two layers of different resistivities was worked out in September, 1928, by W. H. Wise of the American Telephone and Telegraph Co. It has been successfully applied in the explanation of some of our experimental results. Similar formulæ were published by H. P.

* *Elektrische Nachrichten-Technik*, 1930, vol. 7, p. 393.
† *Bell System Technical Journal*, 1930, vol. 9, p. 760.
‡ *Ibid.*, 1931, vol. 10, p. 420.
§ *Journal I.E.E.*, 1933, vol. 72, p. 259.
‖ *Transactions of the American I.E.E.*, 1930, vol. 49, p. 1370.
¶ C.M.I. Document No. 32—12.

Evans,* and formulæ for the case of lines of finite length with a 2-layer stratified earth were published by Riordan and Sunde.† In Table 4 a comparison is made between measured and calculated values of induced voltages in certain open-wire lines inductively exposed to the Carlisle–Lancaster 132-kV grid transmission line. Similar tests have been made in this country, some of which are reported in Tables 2 and 3 of the Bowen-Gilkeson paper, and in Table 2 of Engineering Report No. 14. Generally speaking, the results obtained have been quite satisfactory. The discussion of the screening action (we term it "shielding") of earth wires on power lines and of power and telephone cable sheaths is of special interest, since there has recently been prepared a report of the Joint Sub-Committee on Development and Research dealing at some length with this subject. In this report, which deals with a number of types of shielding structures, there are presented simplified formulæ and numerous curves by means of which the numerical solutions of many problems in shielding can be readily obtained. In addition, H. R. Moore has written a paper entitled "Iron Shielding for Telephone Cables," which will shortly be published in *Electrical Engineering*. The authors' formula for the screening factor, namely $\lambda = (Z_1 - M_1)/(Z_1 + Z)$, and the separate evaluation of Z, Z_1, and M_1, by the several formulæ presented for these quantities, seems somewhat cumbersome. In all of our work we have expressed the shield factor (the authors' "screening factor") in terms of the self-impedance of the complete shielding circuit and the mutual impedances between disturbing, disturbed, and shielding circuits. For convenience in computations and in experimental work, in order that the results may be applied under all circuit conditions, we separate the self-impedance of the shielding circuit into two components—the "internal" and the "external." The internal component is that due to the resistance drop along the conductor and the linkages of such flux as is entirely within the (cylindrical) conductor; it is the ratio of the voltage drop along the outer surface of the conductor to the total current in it, and can be determined experimentally by direct measurement of these two quantities. The external component is the impedance with earth return of a thin-walled, perfectly conducting, cylindrical conductor with radius and location the same as those of the shielding conductor; it is calculable by Carson's formula or the curves of Engineering Report No. 14 referred to above. The mutual impedance between the shielding circuit and the disturbing or disturbed circuits is similarly separated for power or telephone cables. This separation of the impedances into components lends itself particularly well to the treatment of cable shielding problems, especially where the cable sheaths are surrounded by magnetic material such as steel tapes, where the impedances are variable with current and must be experimentally determined. The difference between our procedure and that followed by the authors is considered by Trueblood and by Whitehead and Morgan in their discussion on the paper by Clem.‡ We have had no difficulty (such as might be inferred from the comment of Whitehead and Morgan) in applying our methods to problems of multiple-earthed earth wires and underground cable sheaths where the current varies with the location along the line. The results of some experimental determinations of earth-wire currents were described by Grueter in a discussion on Clem's paper. The authors employ two units for specifying the electrical characteristics of the earth, C.G.S. units for the conductivity and the ohm-cm for the resistivity. We have found the use of C.G.S. units rather awkward for practical work, and the ohm-cm is inconveniently small. We therefore now use almost exclusively the metre-ohm as a unit for specifying earth resistivities, having abandoned the C.G.S. unit in our practical work. A number of geophysicists also have found the metre-ohm most convenient for their work, and I should be very glad if it commended itself for use by European engineers. European and American practices differ, as pointed out by the authors, in the unit employed for expressing coupling. To treat mutual inductance as a complex quantity seems to be inconsistent with long-established usage of self-inductance as a real quantity. Furthermore, there does not seem to be any practical gain to be derived from such a convention. Impedances, both self and mutual, may be complex; hence providing all necessary means for expressing both the magnitude and the phase angle of the coupling between two circuits. It is my hope, therefore, that European engineers will adopt the more consistent usage of mutual inductance as a real and not a complex quantity. The authors cite the book, "Inductive Interference," published by the California Railroad Commission in 1919, as a source of methods for evaluating the induction from balanced currents in a power system. For the benefit of those who may refer to the California reports, an error in formula 39 of Technical Report No. 64, as printed on page 655, should be corrected. In that formula, giving the induced voltage due to balanced currents, both logarithms should be squared, and not the first alone, as printed. This error does not occur in the forms which are given in that report for systematizing such computations. Both formula and forms take account of the effect of currents in the earth on the "ground plane" theory. It is true that in many instances of small separations of power and communication conductors the effect of the currents induced in the earth by the balanced phase-wire currents may be neglected, though as the separation increases the effect becomes of progressively greater importance. I therefore see little advantage in defining "direct induction" as that due to the currents in the wires alone, exclusive of the earth currents. The authors suggest that often sufficient information as to the resistivity of the earth may be deduced from the geological structure. Work of this sort has been carried forward in this country, and some preliminary results have been reported by R. H. Card.* I believe, however, that much remains to be done before it will be possible to translate geological data directly into resistivities useful for computing coupling for engineering purposes, particularly for larger separations of lines.

Dr. H. Klewe (Germany) (*communicated*): The *frühter*

* *Physical Review*, 1930, vol. 36, p. 1579.
† *Bell System Technical Journal*, 1933, vol. 12, p. 162.
‡ "Reactance of Transmission Lines with Ground Return," *Transactions of the American I.E.E.*, 1931, vol. 50, p. 901.

* *Transactions o the American Geophysical Union*, 1933, p. 111.

(coherer) protective device has been introduced in Germany, where exposures 10 to 20 km in length and having a separation of the width of a street are met with in rural electrification at 15 kV. Earth faults, giving rise to loud acoustic shocks on the telephone system, occurred so often after a certain time that precautions became essential. If the high-voltage lines had had an earthed neutral the noises would have probably been more intense, not weaker. With rectifiers, according to our experience (which is in agreement with the English measurements) the form factor of the current is not of great importance because the apparent impedances of the current circuit for direct current and alternating current respectively vary differently and independently of each other. The harmonic current, on which alone the interference depends, is, to a large extent, independent of the direct current. The conclusion to be drawn from this is that the T.I.F. (and the relative interference) decreases first of all with rising current, subsequently increasing as overload increases distortion. If a rectifier feeds several lines, only one of which runs parallel to the telephone conductors, then the disturbance on the latter depends on whether the disturbing voltage remains constant or changes with the load on the other lines. Similarly with constant direct current on the first line the interference will vary at the same time as the T.I.F. If the interference current is introduced the picture becomes complicated. The authors' data as to the relation between the harmonic voltage and the disturbing voltage with rectifiers agree with the observations made in Germany. The dependence of the "mean" conductivity of the earth on the frequency in the German mutual-inductance tests is in my opinion to be attributed entirely to the fact that the earth is stratified and that the depth of penetration depends on the frequency. The data concerning the screening effect of an earth wire on high-voltage conductors are in accord with our experience. We have occasionally used a phase conductor itself as substitute for an earth wire, and have thus obtained a screening factor of 0·6 (at 50 cycles per sec.). On the other hand, I think it improbable that the induction effect could be reduced to $\frac{1}{3}$ or even $\frac{1}{4}$ by means of several good conducting earth wires. Formula (9) for the screening effect of rails is not clear to me. According to this formula the induction effect for a very large number of rails would practically disappear. In my opinion, however, the compensating effect of a larger number of conductors is limited by the fact that the inductance of the bundle of conductors is not in any way small. We explain the low values of the screening factor in our measurements on a railway with a third rail by the fact that in this case the distance between the current and track rails is very small. On this account the mutual inductance M_1 between these two rails is very large, and according to formula (8) the screening factor becomes very small. In formula (9), M_1 is neglected.

Mr. K. L. Maurer (U.S.A.) (*communicated*): The authors' discussion of interference caused by a.c. traction systems lays emphasis on noise-frequency, rather than fundamental-frequency, interference. In American experience with a.c. traction systems the relative importance of these types of interference is the reverse. This naturally alters the relative importance of the factors of the problem and thus of the methods of treatment, which it may be of interest to describe. In dealing with long feeding distances and long uniform exposures, it is usually permissible to take the earth current at its limiting value, namely $(1 - \mu)I$, where I is the trolley current and $1 - \mu$ is a factor similar to the screening factor employed by the authors. There are, however, a number of types of situations where end effects are important, such as short feeding distances, and discontinuities in the track circuit such as substation earths and interruption of track. These end effects include both the reduction of the average earth current over sections near short-circuit or substation points and the production of earth potentials in the same area due to conduction through the earth of track leakage currents. The determination of track current distribution with end effects included has been put on a systematic basis by J. Riordan.* In the notation of that paper the factor $1 - \mu$ mentioned above is given for single-track systems by the formula $1 - \mu = 1 - Z_{12}/Z_{22}$, where Z_{12} = mutual impedance per unit length of trolley-earth and track-earth circuits, and Z_{22} = self-impedance per unit length of track-earth circuit. For multi-track systems a similar formula may be used, when the meaning of the impedance is extended; thus Z_{12} is the mutual impedance per unit length of the trolley-earth system and the return system, and Z_{22} is the self-impedance per unit length of the return system. These formulæ, it appears, are not identical with the single formula for the screening factor given by the authors. Their statement that end effects extend $\frac{1}{4}$ to $\frac{1}{2}$ mile appears to need qualification; for example, with a single-track road having 130 lb. rails and a leakage conductance of 1 mho per mile, Fig. 4 of the paper mentioned above shows that the end-effect currents reach negligible values only after 4 miles. Earth potential arises from the leakage of currents from the track into the earth and is thus exclusively an end-effect phenomenon. No general formula has been published to our knowledge, but in the neighbourhood of a point of short-circuit at some distance from both feeding substations the earth potential may be calculated approximately from

$$V = \rho\gamma I\left(\log_e\frac{1\cdot 12}{\gamma y}\right)10^{-4}\,\text{volts}$$

where ρ = earth resistivity in metre-ohms, γ = track propagation constant per mile, y = distance in miles from point of short-circuit, and I = trolley current in amperes. For single-track roads, high earth resistivity, and circuits terminated close to the railroad, the voltage derived from earth potential may exceed the voltage magnetically induced.

Mr. G. E. E. Swedenborg (Sweden) (*communicated*): The induced voltages produced under normal conditions by power circuits paralleling communication circuits are often chiefly due to currents circulating between the power system and the earth. This being so, it is important to know the current intensities in the earth connections of the power system. The authors state that, at Portobello, neutral currents not exceeding 3 or 4 amperes were measured; the 3rd and, to some extent, the 5th

* *Transactions of the American I.E.E.*, 1932, vol. 51, p. 1011.

harmonic together with the fundamental forming the majority of the neutral current. I should like to ask whether the power system in question is transposed and, if such is the case, what are the distances between the transposition points. Further, when new power lines are constructed, are they transposed? That transposition may be of great importance as regards the value of the neutral currents was manifested in a characteristic case on a Swedish 70-kV system having an extension some hundreds of kilometres in length. Some years ago an inductive coil of the Petersen type was inserted at the neutral point of a transformer on this network. The purpose was to bring about a rapid extinction of the arc when flash-overs occurred due to steep voltage waves, caused by lightning phenomena, and in this way to avoid disturbing interruptions of the service. To this end the coil was tuned to resonate with the capacitance of the power system. Previously this system had been connected to earth by means of a non-inductive neutral resistance of 600 ohms. After the coil had been inserted there arose, however, a considerable amount of induction in the communication circuits parallel to the power line. Although the separation was of the order of several kilometres over a parallel of about 30 km, the induction voltage attained the value of 50 volts, and single-wire telegraph circuits with earth return of course suffered considerable interference. It was stated that a current of about 30 amperes passed the induction coil. The remedy was complete transposition of the entire power system with several transposition sections (barrels). By this procedure the neutral current was reduced to about 3 amperes. In order to limit the current still further, the earthing system has been so arranged that normally the above-mentioned neutral ohmic resistance shall be in circuit, but that it shall be automatically disconnected when earth faults occur, whereupon the Petersen coil will bring about the desired extinction of the arc. The reason why the impedance unbalance between the phases is of such importance as regards the neutral current, when the Petersen coil is utilized, lies of course in the fact that a residual voltage will in this case (resonance tuning) produce a relatively large neutral current. I have learnt that on English power systems direct earthing is favoured. Although this practice will probably result in comparatively high current intensities when earth faults occur, it may not be dangerous from the point of view of the communication circuits provided the power lines are built cross-country and not along the public highways. In other countries, however, where from topographical or other reasons power lines and communication lines often have to run parallel over long distances, it may be desirable, from the point of view of interference, to reduce the currents to earth to the greatest possible extent. On the Swedish power systems the neutral point is in general not directly earthed. When important new power lines are constructed they are almost always transposed. The transpositions are carried out in accordance with the C.C.I.F. Directives, with limited transposition sections in order to reduce effectively the residual voltages and currents to earth not only of the fundamental but also of the harmonics. With regard to the screening effect of the cable sheaths, the authors say that armoured cables afford a greater reduction in the induced voltage than unarmoured cables. This applies to the fundamental and the most important harmonics. During the course of experiments carried out in Sweden some years ago it was stated, in regard to a representative case where normal long-distance cable constructions were employed, that the superiority of armoured cable is maintained up to about 2 500 cycles per sec., but at higher frequencies the unarmoured cable gives better compensating effect. The thickness of the lead sheath was the same for both cables. This instance illustrates the effect of the highly increased resistivity of the sheath of armoured cables as the frequency is gradually increased. The paper mentions that at most crossings with power lines the telephone circuits are placed underground. It would be of interest to know whether special types of cable construction are used in such cases, in order to avoid reflection phenomena and amplifying difficulties due to irregularities in the impedance curves of the telephone circuits. It is possible that the insertion of a number of cable sections in open-wire circuits would adversely affect carrier telephony.

[The authors' reply to this discussion will be found on page 235.]

South Midland Centre, at Birmingham, 4th December, 1933.

Mr. H. Faulkner: The paper is one of fundamental importance to communication engineers. It shows how unwanted noises may be introduced into communication circuits from power circuits, gives examples of "telephone interference factors" which can be expected of well-designed machines in practice, indicates how reductions in interference can be achieved on both the power and the telephone sides, and explains how the interference to be expected in certain cases can be calculated; but I do not see how this information is finally brought to bear on the practical problem. Perhaps the authors could give a brief sketch of the machinery available for that purpose. There are a few details to which I should like to refer. First, in the weighting curve in Fig. 1 there is a decided peak in the neighbourhood of 1 000 cycles per sec. In these circumstances why was 800 cycles per sec. chosen as the reference frequency? It seems to me that 1 000 cycles per sec. would have been a more logical choice; and I believe that this frequency is used as a reference frequency in the United States. Incidentally, I observe that although the C.C.I. has carefully provided limits within which to work, the filter shown is outside those limits. As regards noise measurement in the telephone line, the position in the circuit where such noises are to be measured is not clear. The amount of noise which is to be taken as tolerable in a telephone circuit is not quoted, nor is any reference made to the speech level in the circuit. In commercial radio-telephone links where the noise is uniformly spread over the band and arises

from atmospherics—or from receiver noise when very low field strengths are being received—measurements of the signal/noise ratio are used extensively and form one of the bases on which the commercial value of the circuit is judged. A signal/noise ratio of 12 decibels will just give an intelligible commercial circuit; but this value involves considerable annoyance and would not be acceptable on comparatively short trunk communications, the psychological factor of speaking half-way round the world being absent. Then, again, a better standard still is demanded on those land-line circuits which are used for broadcast purposes. It seems to me that signal/noise ratios should be laid down for both these cases. Difficulty will no doubt be met where both classes of service have to be supplied by circuits on the same route or in the same cable. Nevertheless, the service has to be given, and if standards were agreed and laid down we should know where we stood. With regard to mercury-vapour rectifiers, it is observed that the use is recommended of shunts resonating to the principal interfering frequencies. I presume the authors are satisfied that this is a better or, perhaps, more economical solution than the use of smoothing circuits of the low-pass filter type which are adopted extensively in connection with rectifiers supplying the anodes of radio-valve transmitters with H.T. direct current. With regard to the measurement of earth resistivity, fairly simple means are available to the radio engineer, by measurement of the "tilt" of the radiated wave-front. Probably this method, which was developed, I believe, at the National Physical Laboratory, is not applicable to the low-frequency case, but I mention it as a matter of interest. As regards induction from earth currents, I see that the case of the balanced or nearly balanced telephone pair is now being investigated by the C.M.I. This seems to be the most important case for the telephone engineer, and the result of this investigation should provide further very useful data.

[The authors' reply to this discussion will be found on page 235.]

North-Western Centre, at Manchester, 21st November, 1933.

Mr. T. E. Herbert: It is particularly unfortunate that the resistivity of the earth should be an essential factor in the calculation of the results of a fault earth-current. Earth-resistivity values vary enormously, and the figure found in the Isle of Man is even higher than that observed at Shap. Fortunately, in the Isle of Man the transmission voltage is only 33 kV. It would be interesting if the authors would indicate the effects on the earth resistivity of variations in the geological conditions. For example, it seems quite within the bounds of possibility that, over a long stretch of route, conditions may vary between the lowest and the highest earth-resistivity values in a quite unpredictable fashion. If this is so, either a great many measurements must be made or, alternatively, the problem must be abandoned and the conditions to be met must be determined by actual trial with reduced currents. Mr. A. J. Jackman* has described a method of calculation, based on the equivalent earth-plane theory, which seems to be in general agreement with the experimental curves. The mathematical analysis of Mr. Josephs suggests, however, that the theory is wrong in conception and principles. I should like to know whether the simplified methods of Mr. Jackman are acceptable to the authors. In my opinion long open trunk lines will eventually disappear. The problem of interference between power lines and lead-covered cables, however, is much more serious. Undoubtedly it would be very costly to replace existing cables by new ones, either armoured, screened by copper tapes, or carried in iron or steel pipes. Another solution of the problem might consist in the substitution of direct current for alternating current on the grid, but this is a matter for the very remote future.

Mr. A. H. C. Knox: If a power line runs over soil of high resistivity and a parallel telephone line runs over soil of low resistivity, is it correct to base the induced-voltage calculation on the low-resistivity soil only, neglecting the effect of the soil under the power line? On page 210 the authors state that the induction may be reduced to one-third or one-fourth by using two earth wires. Has this practice been adopted in any bad cases in this country? Where two 132-kV lines and two 33-kV lines are erected on one line of towers, would a heavy fault current in one circuit be capable of inducing such heavy out-of-balances in the others as to shut them down?

Mr. A. B. Field: The expression "weighting curve" applied to Fig. 1 would be more happily applicable to a curve deducible from it, but in which the ordinates plotted against the present abscissæ represented factors by which disturbing effects of different frequencies had to be multiplied to make them comparable. One is inclined at first to ask as an addition for a re-draft of Fig. 1 in a form directly comparable with Osborne's weighting curve.* It is perhaps just as well, however, not to have the information too ready to hand, as the work of obtaining it for oneself brings home the large element of uncertainty which necessarily remains in making practical deductions, and which tends to be masked by the precision of the curves and the data. The curve of Fig. 1 is applicable to the telephone circuit, and in determining the method of its application to the power circuit or to the machine terminals we have to consider the way in which the effect is transmitted from the one to the other. The problem is complicated by many uncertainties, as is illustrated in the first column of page 204, where the authors debate whether in passing from its application to the telephone circuit to its application to the machine terminals the weighting deducible from Fig. 1 shall be multiplied by the frequency; they conclude that, for the conditions in this country, on the whole it is just as well not to multiply by the frequency. Since we are dealing with phenomena covering a range of frequency of, say, 300 to 2 000 cycles per sec., this casual decision affects the relative results at extreme frequencies to the extent of some 600 per cent. Let us then be on our guard

* *Post Office Electrical Engineers' Journal*, 1933, vol. 26, p. 97.

* *Transactions of the American I.E.E.*, 1919, vol. 38, p. 265.

against attaching too much importance to a 10, 20, or 30 per cent departure from a stipulated T.I.F. figure for a power line or piece of apparatus. Turning to the definition of equivalent disturbing voltage, we find that for a power line this is "the e.m.f. at 800 cycles per sec. which, when applied to a power line, produces in a neighbouring telephone line the same disturbance as the operating voltage of the power line with all its harmonics. . . ." How is this 800-cycle e.m.f. to be applied? In the general case of three or six lines, with their earth wires, is it to be applied between one line and earth, between all three or all six in parallel and earth, between one or several lines and one or more other lines in parallel, or is it to be a polyphase application? In connection with the consideration of the features of transfer of interfering effects from power to communication lines, a little information would be very useful as to the relative reactance and resistance components of the impedance at one or two typical frequencies of the standard telephone receiver, or of the receiver referred to in the footnote on page 202 (column 2). It would also be interesting to know the make-up of the 600-ohm impedance referred to.

(*Communicated*) I should like to refer to the way in which frequency enters into the transmission of disturbance from a power to a telephone overhead line. The following statement indicates the nature of the factors which we must apply to the magnitudes of the voltage harmonics in the power line when considering the effect in a neighbouring telephone line as measured by the voltages across a receiving apparatus in it. (1) For electrostatic induction between power and telephone lines: (*a*) When no current is drawn from the telephone line, this circuit being open, or (in an abnormal hypothetical case) when the capacitive impedance between power and telephone lines is very small in comparison with the impedance in the telephone line circuit, the factor involves frequency to index zero. (*b*) In the normal case where the impedance relations are the reverse of those indicated under (*a*), the factor mainly involves frequency to index unity. At higher frequencies, say above 1 200 cycles per sec., a very minor additional term involving frequency squared appears; at lower frequencies the relation is a little erratic owing to the peculiar impedance characteristics of the normal telephone receiver. (2) For electromagnetic induction between power and telephone lines, assuming the harmonic currents in the power line to be related to the corresponding voltages in accordance with a predominance of reactance in the power circuit: In the normal case, the conditions are the same as those of (1) (*b*) with the index reduced by unity; i.e. the factor is substantially independent of frequency.

Mr. W. Stretch: The authors state that the Post Office noise meter gives a reading corresponding to the r.m.s. value of the noise voltage in the circuit. In order that this shall be the case, it is necessary to take certain obvious precautions in the choice of the rectifier and in the design of the amplifier. The majority of rectifiers follow the square law over only a small portion of their characteristic, and if certain limits of input are exceeded the response becomes nearly linear. Does the P.O. meter incorporate a means of controlling the amplification, or has it been found possible to design a rectifier which gives the square-law response over a large range of input voltages? I assume there would be no difficulty in producing a rectifier with a linear characteristic, which would measure mean values, or with any other characteristic between the linear-law and the square-law type, if such a characteristic appeared to be desirable. As the authors suggest, however, it may be that the voltage components are not additive in regard to their disturbing effects. Turning to the question of voltages induced in telephone lines by fault currents, I imagine that the electric shock is not likely to be of a serious nature if the voltage is limited to 300 volts, having regard to the impedance of the couplings between the power circuit and the telephone circuit and to the short duration of earth-fault currents. On the other hand the acoustic shock might be serious, though it would depend on the steepness of the wavefront. I should like to know whether the authors support this view. The copper-oxide rectifier referred to in the paper appears to be particularly effective for suppressing sharp impulses of short duration. It also possesses the advantages of extreme cheapness, simplicity, and reliability. If it is connected in the simplest way, namely in shunt with the receiver, it cannot interfere with the signalling conditions and the transmission loss is negligibly small, when used in conjunction with apparatus of the usual impedance values. Perhaps the authors will say whether on repeatered lines the presence of the valves would limit the energy sufficiently to avoid acoustic shock. In dealing with proximities and parallelism between power transmission lines and telephone lines it is usual to calculate the voltage induced under earth-fault conditions. Is it safe to assume that provided the induced potential does not exceed 300 volts under fault conditions there will be no appreciable telephonic disturbance under the normal conditions of operation? The best method of avoiding interference is, of course, to remove the source; that is, to correct unbalances wherever they occur. Another method which has been tried between telephone circuits is deliberately to introduce couplings at the ends of the circuits, which transfer energy from the disturbing circuit to the disturbed circuit, in such a way as to neutralize the disturbance picked up along the line. The method might have an application in certain cases of interference between power and communication circuits; for instance, where single-wire or earth-return telegraph circuits run along an electrified railway, or where communication or control circuits are run on the same towers as the power transmission lines. Has any attention been directed to this possibility?

Mr. G. L. Porter: The authors state that consideration has been given to disturbances caused by harmonics during normal operation of the power system and to danger due to excessive induction at the fundamental frequency under transitory fault conditions, but they do not mention the induction occurring during the discharge transient at the instant of breakdown. Even where it was oscillatory the frequency would be altogether independent of the fundamental frequency or harmonics of the power system. In cases of direct

magnetic induction and where the screening is not great the induced voltage may be serious, and surely merits a reference in the paper. Regarding the copper-oxide type of acoustic-shock absorber, a large number of these have been placed in service by one telephone administration, and in view of the convincing demonstration of their effectiveness given at the official opening of the new research station at Dollis Hill it would appear that the British Post Office is at last becoming interested in this absorber. It is of particular advantage in dealing with the steep-fronted transients which occur when the telephone switching apparatus is not functioning properly, and as acoustic shock from this source appears to be the only kind to which operators in this country are exposed it is rather surprising that the Post Office have not yet installed such absorbers. In Table 11 the induced e.m.f. falls with rise in frequency; I take it that this effect is due to change in the screening factor, and that where there is severe exposure to the primary magnetic field and little screening—as in the case of telephone cable suspended from a catenary on the actual power line—the curve is likely to slope the other way.

Mr. B. L. Goodlet: The paper contains no reference to interference from transformer magnetizing-current harmonics. I understand that some trouble has been experienced owing to the use of excessive core inductions, and I should like to know whether the authors can give any information about this matter.

Lieut.-Col. K. G. Maxwell: In view of the wide range of other variables dealt with in the paper, I should like to ask the authors whether they have ever found an appreciable effect upon the values of earth-path resistivity by reason of the extremes existing due to very dry summer or drought conditions and, on the other hand, flood conditions such as are frequently experienced locally in this country.

Mr. J. W. Thompson: I should like to draw the authors' attention to a rather peculiar case of interference on an overhead trunk line, due to an underground power cable on the other side of the road. The pole earth-wire, a cross-road stay, and the ground stay from the stay pole, formed an earthed loop, as shown in Fig. A. The power cable was laid within the loop close to the ground stay and, of the 24 circuits carried by the overhead route, only 4 circuits, which were also within the loop, were disturbed. Immediately the continuity of the loop was broken by separating the stays at the stay-pole, the interference ceased and was not again observed. On the assumption that the static field of such a cable does not extend beyond the sheathing, it would appear that a current was induced in the

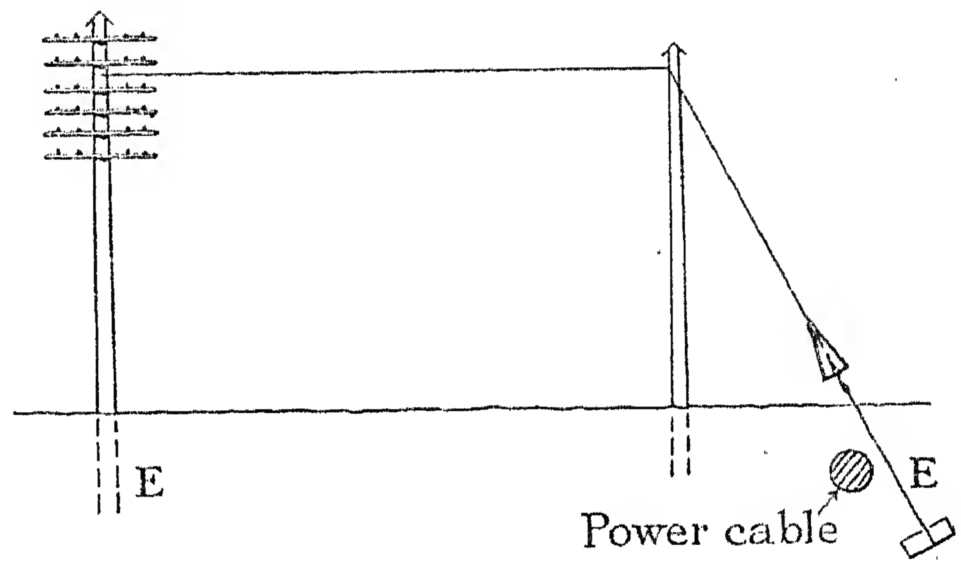

Fig. A.

iron stay-rod by the magnetic field of the power cable, which was known to be unbalanced.

Mr. G. G. L. Preece: I am interested in the effect of mercury-arc rectifiers on telephone interference; I take it that most of the experiments on this subject which the authors made were in connection with 6-phase mercury-arc rectifiers. Mercury-arc rectifiers of the glass-bulb type, having a 12-phase connection, cause no interference, and wave filters make very little difference when used in connection with this type of rectifier. I was interested in Mr. Herbert's reference to changing over to high-tension d.c. transmission. While this would cure a great deal of the trouble, it might possibly create others. It is an interesting possibility, already a little beyond the experimental stage, and I am not at all sure that it may not eventually become an accomplished fact.

The Authors' Reply to the Discussions at London, Birmingham, and Manchester.

Mr. W. G. Radley and **Dr. S. Whitehead** (*in reply*): The change from a subjective to an objective method of measuring noise, mentioned by Mr. Bartholomew, has meant considerable progress in the study of disturbance from power systems. In reply to Mr. Field, the frequency weighting curve (Fig. 1), on which the objective method is based, was obtained by experimental determination of the voltage across a receiver at various frequencies to cause a given loss of articulation. It therefore takes into account the effect of variation in the impedance of the receiver together with the greater effect of receiver resonances. Figures showing the variation of impedance of a standard Bell receiver when held to an artificial ear are given in Table B.

In practice the impedance of telephone receivers of other types (including that used in the hand micro-telephone) will show the same general kind of variation, so that the weighting will not change greatly on this account. Since the noise meter behaves as a high-resistance voltmeter of constant input impedance, the conversion from a scale of voltage ratios to a decibel scale, as regards

Table B.

Frequency	Resistance	Reactance
	ohms	ohms
700	142	145
875	170	160
1 040	192	132
1 360	175	190
1 750	210	225
2 750	220	275

the instrument itself, is legitimate. This conversion gives the convenience of logarithmic plotting. The values given by the curve of Fig. 1 may be restored to

a scale of ratios in the manner indicated by the footnote in the first column of page 202.

The attenuation introduced by a standard Post Office exchange cord circuit, local line, and subscriber's set, is shown in Table C. Less variation is found in other types of British exchange circuits, and quite different results are obtained with the terminations appropriate to other countries. This is an argument against the use of a network having a modified attenuation/frequency characteristic for making engineering measurements on power plant, although, as Mr. Blye states, it has been decided on in America. On the other hand, a circuit model with an attenuation/frequency characteristic similar to that of the circuit in use is normally added when measurements are made at the terminals of Post Office trunk or junction lines. When measurements are made on the power line, the error introduced by the wrongful omission, or inclusion, of the frequency factor will not be so great as that suggested by Mr. Field. The factor is $f/800$, so that the error will only be large when a single low-frequency or a single high-frequency component comprises the greater part of the disturbance. Considerable tolerance is allowable when variations in measurements or deviations from prescribed values are expressed on a percentage basis, since the effect of noise on the ear follows a logarithmic law. With regard to the measurement of a complex noise, the amplification in the Post Office circuit noise-meter is controlled, so that the rectifiers only operate over that small portion of their characteristic which follows the square-law curve. The manufacture of a standardized and comparatively cheap form of circuit noise-meter has been envisaged by the C.C.I.

Answering Mr. Faulkner and others, the maximum permissible amount of noise has not yet been entirely determined. For subjective measurements made at the end of a trunk line and in accordance with the footnote on page 202 (col. 2), the C.C.I. Directives give a limit of 5 millivolts for open-wire circuits and 2 millivolts for cable circuits. The effect on the intelligibility of a conversation depends on what is known to the radio engineer as the signal/noise ratio. Captain Timmis mentions the practical difficulties which lie in the way of determining this ratio for telephone lines. It must not be forgotten, however, that the effects of induced noise are twofold: the intelligibility of the received speech is reduced, and also considerable annoyance may be caused to the telephone user. It has been provisionally agreed by the C.C.I. that power noise on international lines should not cause a greater loss than 5 per cent in (logatom) articulation; but when both speech and noise are loud the annoyance factor may become important. For this reason we consider that under no condition should the noise, when measured across the terminals of the receiver, exceed the equivalent of 1 millivolt at 800 cycles per sec. The latter was chosen by international agreement as the standard reference frequency for Europe.

The term "Telephone Interference Factor" is used in the paper in place of the C.C.I. expression "Telephone Form Factor," to which it is numerically equivalent. The numerical values quoted have the advantage of being expressed on a percentage scale instead of in terms of arbitrary units, and of being measured in accordance with modern recommendations on a circuit noise meter. Otherwise they fulfil exactly the same function as the values measured on the original T.I.F. meter which included Osborne's weighting network.

So far there has been no demand in this country for devices primarily to give protection against acoustic shock from power systems. For some years the Post Office have been studying the application of rectifiers as voltage limiters for reducing acoustic shock. Careful note is also being taken of the experience of other administrations with the various types of shock absorbers mentioned in the paper and in the discussion. On repeatered telephone circuits, saturation of the valves will definitely limit the shock passed. The limitation of the induced voltage under fault conditions to 300 is based on the generally accepted operating value for protectors, and not on considerations of the voltage dangerous to life. Protectors are connected to every open-wire Post Office line. With reference to the remarks made by Mr. Marshall and Mr. Kapp, we are pleased to be able to state that no injury caused by induction from the Central Electricity Board's grid system has yet occurred to Post Office staff. It has to be noted, however, that in both Europe and America linemen have been killed by power induction. Statistics are not available of the number of disturbances due respectively to short-circuits on power lines and to lightning. Both causes of trouble are very rare in this country. It can be definitely stated that no member of the public, or of the staff, has been either killed or very seriously injured by lightning striking the Post Office system. Post Office linemen are expected to exercise due caution, and printed instructions give warning against working on an overhead line during thunderstorms.

It cannot be assumed that, provided the induced voltage does not exceed 300 volts under fault conditions, there will be no appreciable disturbance under normal conditions of operation. For the 132-kV lines of the grid system this has been found to be so, but for older and lower-voltage systems very different conditions exist.

TABLE C.

Frequency	50	150	300	500	1 000	1 500	2 000	3 000	4 000	5 000
Attenuation (decibels) ..	54	28	11	9·5	7·2	6·0	4·8	4·5	3·7	2·9

Problems associated with the question of single earthing, multiple earthing, or insulating the neutral, are referred to by several contributors to the discussion. The neutral currents observed by us in Great Britain have been lower than those apparently met with in Sweden, 5 amperes being large for a transmission system. The tests referred to by Mr. Morgan have now been more fully analysed with the help of Dr. Collard, and it appears possible to calculate the harmonic impedance of a system with some confidence. It is hoped later to show that the effect of an additional earthing point in a multiple-earthed system is fairly local. Phase symmetry is often an important factor, but all the C.E.B. lines are transposed one barrel per section, the intervals ranging from, say, 4 to 20 miles. In dealing with such high-voltage lines Morgan and Whitehead in a previous paper* advised transposition for phase symmetry (among other reasons) on single-circuit lines, but suggested that the advantage might not justify the high cost on double-circuit lines. As suggested by Mr. Goodlet, where a high flux density has been used in transformer design, large 3rd and 5th harmonics have been noted by us, and special apparatus is sometimes used to overcome this trouble. We welcome the suggestion of Mr. Carrothers, which might remove the difficulty of restricting fault currents without interfering with protective systems. Rapidity of fault clearance, as may be used on solidly-earthed systems, is not of first importance as regards danger, since experiments by Kouwenhoven and Langworthy† suggest that the duration of shock is not of great importance if it exceeds a fraction of a second.

Mr. Herbert and Mr. Marshall refer to Mr. Jackman's presentation in a recent paper of the original method of calculating the mutual inductance between two circuits by reference to an equivalent earth plane. This method is not discussed in our paper because the picture which it gives of the coupling is not in accord with physical fact. For practical engineering purposes this would not matter greatly if the depth of the equivalent earth plane could be so fixed for a given site that the calculated coupling would always be numerically equal to the true coupling. This cannot be done, and the depth of the equivalent earth plane has to be adjusted as such factors as frequency, separation, and resistivity of the earth, are varied.

We thank Dr. Russell for his very interesting remarks concerning the origin of *ker* and *kei* functions. In addition to the tables referred to in the footnote on page 207, values of *ker′* and *kei′* are given in Table 1 of "Bessel Functions for A.C. Problems."‡ Alternatively, the value of M corresponding to any value of the parameter $x\sqrt{(\sigma f)}$ likely to be met with in practice may be read off directly from the curves of Fig. B.

As implied in the paper, we are in complete agreement with Mr. Marshall and Mr. Ferris in their preference for stating the coupling in terms of a mutual impedance. As, however, much of the work described in the paper had been reported to the C.M.I., it seemed better to retain the European practice and so avoid confusion.

We thank Dr. Collard for his note on the correction of the induced voltage for the transmission coefficients of the telephone line. Strictly speaking, both the power and the telephone circuits should be regarded as transmission networks with distributed coupling, but, for simplicity, they are treated in the paper as short lines. The error which may arise on this account, especially when phase is considered, is pointed out by Mr. Ferris in his remarks concerning the divergence between the theoretical phase angles and those observed at Shap. The values quoted in the report referred to had not been corrected, but this matter will be dealt with more fully in a later paper. Mr. Urmston does not say whether correction was made for the resistance of the line, earth plates, etc., in the test which he describes. The resistance of an earthed communication circuit is frequently greater than that of an a.c. voltmeter; on the other hand, close parallels are favourable to the development of electrostatic induction. Interference in normal operation may be predicted during construction if the harmonic voltages likely to occur are known. The methods of calculation given in the paper then apply. Alternatively, a small generator, reproducing the harmonic voltages, has been used to predetermine the disturbance experimentally when mercury-arc rectifiers were to be connected.

If the earth resistivity varies widely, a long route must be divided into sections accordingly. Where the resistivity under the two lines differs, that under the telephone line chiefly determines the induced voltage. Resistivities appropriate to various geological formations are indicated by Dr. Collard. The resistivity map which is shortly to be published will obviate the possibility of choosing an unsuitable average value for the country as a whole—to which the C.C.I. recommendations might have led—and reduce the necessity for making surveys. The determination of the conductivity of the earth from the relationship between the horizontal and vertical components of a plane electric wave propagated over the earth/air surface is fairly well known. It was given, for instance, in a paper by Zenneck published in 1907.* Values obtained in this way are determined by the conductivity near the surface. For this reason they are not of great value in calculations of telephone interference from earth currents which penetrate to considerable depths (300 to 400 metres for 50-cycle current). Also, changes at the surface due to drought and flood will have no appreciable effect on the mutual inductance between two lines.

In connection with Dr. Klewe's contribution, it may be of interest to state that, using the formulæ for a stratified earth mentioned in the paper, one of us has recently worked out theoretical curves which agree closely with the variation of mutual inductance with frequency found experimentally at Munsingen and Oldenburg. A simple 2-layer stratification was assumed for each place.

The frequency of transient current surges may be deduced from the constants of the power line. Provided this does not exceed 10 000 cycles per sec., Equation (1) or Fig. B may be used to determine the induced voltage on a telephone line in the normal manner. At very high frequencies the Carson–Pollaczek formulæ become

* *Journal I.E.E.*, 1930, vol. 68, p. 367.

† *Electrical Engineering*, 1931, vol. 50, pp. 406, 929; and 1932, vol. 51, pp. 242, 693.

‡ H. B. Dwight: *Transactions of the American I.E.E.*, 1929, vol. 48, p. 812.

* J. Zenneck: *Annalen der Physik*, 1907, vol. 23, p. 846.

inaccurate owing to their neglect of displacement currents.

With regard to the various points in connection with mercury-arc rectifiers and traction systems raised in the discussion, we recommend that each case should be decided on its merits. Equation (13), Fig. 18, and mally given by 12-phase rectifiers since the harmonics are smaller and fewer, being separated by 600 cycles per sec. The four chokes recommended for 6-phase rectifiers represent the cheapest solution, shunt circuits being necessary on account of the high current rating required for series circuits. A.C. distortion by rectifiers

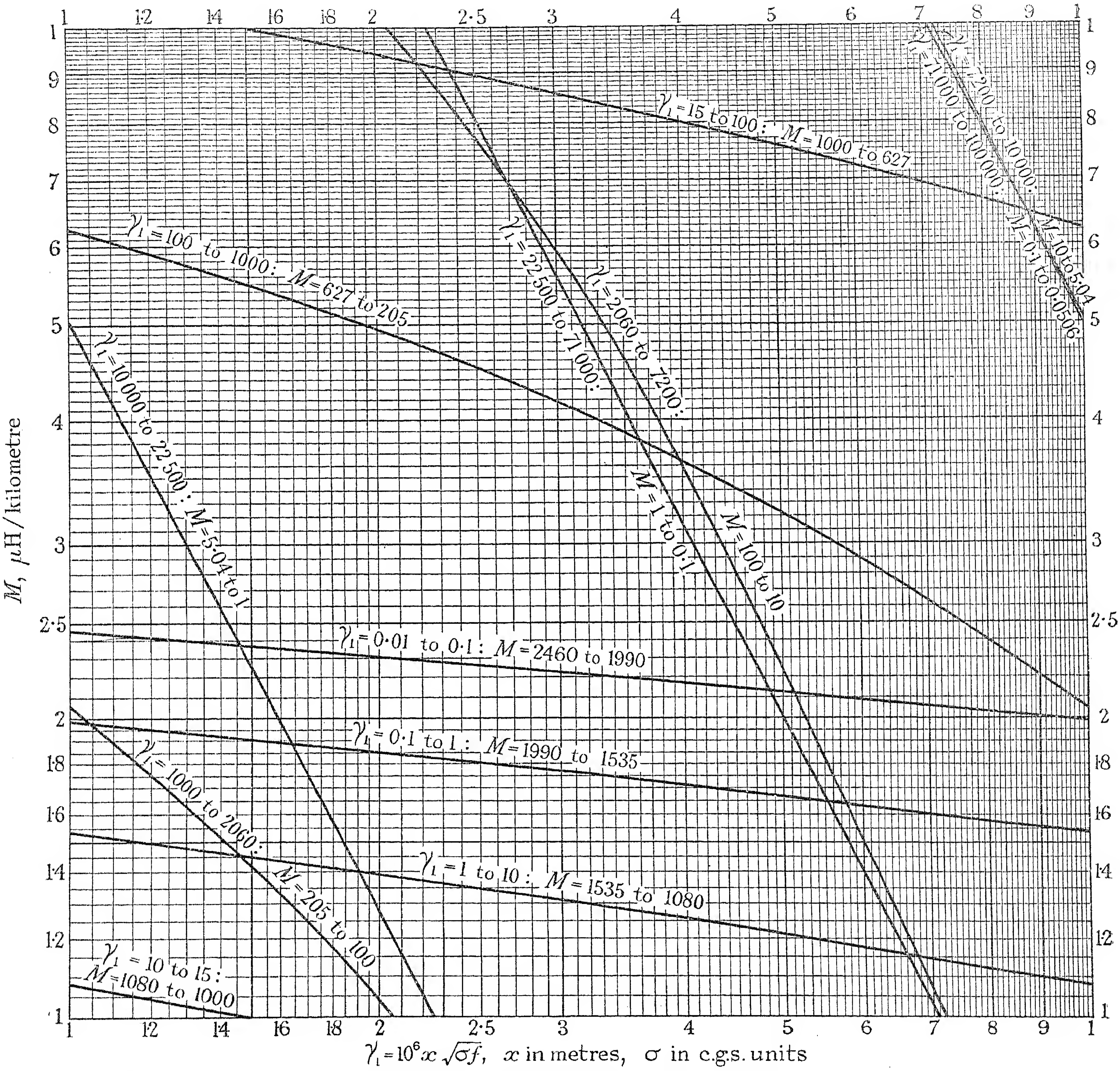

FIG. B.—Curves for the determination of the coefficient of mutual induction M as a function of the separation, of the conductivity of the earth, and of the frequency.

the associated paragraphs, give very simple rules for the purpose. In the instance given in the paper, the T.I.F. of the current was included for ease of calculation, since the voltage and current T.I.F.'s varied in complementary fashion. For general use we agree that, as indicated in Section (2) of the paper, the voltage T.I.F. is the important quantity. Less interference is normally given by 12-phase rectifiers since the harmonics are smaller and fewer, being separated by 600 cycles per sec. is under investigation. Trouble has been experienced on control and metering circuits, but the distortion rapidly decreases as we proceed to sections with transformers separating them from the rectifier. As Dr. Klewe indicates, Equation (8) should be used for third- and fourth-rail systems, the screening factor being reduced by the mutual inductance M_1, so that interference

is very much reduced. Equation (9) is an approximation for overhead contact wires.

With regard to Mr. Maurer's comments on the same subject, we have found agreement, as regards the flow of harmonics in d.c. traction systems, with the formula given. This is theoretically approximate, but, so far, practically satisfactory in the cases tested. It is possible that the earth reference-plane approximation, used in the definition of partial impedances, may account for the difference as compared with Riordan's formulæ. The remarks in the paper which may apply to end effects with a.c. traction are based on theory and Continental experience only, since d.c. traction is the rule in Great Britain. Further investigations on third-rail and other systems are envisaged by the E.R.A. to complete the studies so far made. The rails generally diminish induction from external sources, but may canalize the earth current at a point near a power line and carry it to distant portions of the track, giving a net increase in disturbance. As stated in the paper, the rail current is the important factor.

In reply to Mr. Marris, it appears that single phase-to-earth faults are the most frequent type of faults involving earth currents. Statistics, admittedly incomplete, which have been collected, suggest that the double type has only about 10 per cent of the frequency of the single type. In reply to Mr. Knox, induction in other phases must certainly be taken into account during faults, and we have made measurements verifying our calculations. An account will be found in the Bibliography (Nos. 11, 16, 17, 24, and 26). Mr. Stretch's suggestion of neutralizing couplings would not be usually favoured, since it involves apparatus in which power and telephone lines are associated. We note with interest the case of interference which Mr. Thompson describes.

In conclusion, we wish to express our gratitude to those whose contributions to the discussion have materially increased the value of the paper. From an economic standpoint, the justification of the paper lies in the fact that the experiments in which we have been privileged to take part enable interference to be estimated quantitatively and so reduce the expenditure on prevention to a minimum. It is pleasing to note that the data supplied from other countries are in general agreement with that given in the paper.

WESTERN CENTRE: CHAIRMAN'S ADDRESS

By A. NICHOLS MOORE, Member.

"THE ELECTRICITY SUPPLY INDUSTRY AND THE NEED FOR CO-ORDINATION IN ECONOMIC POLICY."

(*Address, abridged, delivered at Cardiff*, 16*th October*, 1933.)

I suppose it is the usual experience of every Chairman of the Institution that so much information is now available on every conceivable subject allied to the electrical industry that it is extremely difficult for him to provide a topic of real interest to all sections and to introduce into his Address anything definitely new. Perhaps in these practical days it is mostly what we are personally interested in as a means to our livelihood that becomes the all-absorbing consideration in our daily life. We have our hobbies and our social interests, but we have always to return to those means whereby we can obtain the necessities and enjoy the comforts of life; and the extent to which we are able to do this depends entirely upon the operation of economic laws for or against us. In this direction, therefore, we have something of vital interest to us all.

Economics has been defined as the study of mankind in his ordinary business of life, and our interest in economic laws lies in the fact that they apply to us universally. They are the laws that govern the world's trade and the activities of every man in the daily process of getting a living.

Greatest perhaps among the laws of economics are those of supply and demand, utility, and price. The trade of the world is weighed by the scales of supply and demand through the controlling mechanism of price. Supply occupies one side of the scales and demand the other. As the scales are operated, inequalities between supply and demand are dealt with by the mechanism of price, which, by moving upwards if the demand side is too heavy for the supply side, and downwards if the supply side is too heavy for the demand side, tends to remove the inequalities between supply and demand and to balance the scales. Utility increases or reduces supply and demand, and thus modifies the operation of the mechanism of price. In world trade it is therefore the controlling mechanism of price which is the supreme factor.

The industrial depression is the result of failure to balance the scales of supply and demand through the controlling mechanism of price, the supply side heavily outweighing the demand side, and as the depression is affecting every industry in one way or another, it is a matter of grave concern to us all.

The balancing of the scales of supply and demand will depend entirely upon whether the controlling mechanism of price is operated upwards or downwards. From the point of view of the seller, prices are the index of the sacrifices that he is prepared to make in order to effect the largest sale of his product, while leaving to himself a sufficient margin of profit. From the point of view of the buyer, prices are the index of the sacrifices that he is required to make in order to obtain the products he needs or desires. High prices repel demand and low prices attract it. The less spent upon one commodity, the more can be spent upon other commodities. An industry that charges too high a price for its commodity therefore not only restricts the demand upon itself, but also, by taking from the buyer an undue proportion of his purchasing power, restricts his demand upon other industries and prolongs the industrial depression. The balancing of the scales of supply and demand through the controlling mechanism of price is the greatest of our industrial problems, and until it is done to the satisfaction of industries in general a real industrial prosperity is unattainable.

My purpose in concentrating upon the fundamental economic laws of supply and demand, utility, and price, to the exclusion of other economic laws and such important allied problems as currency, tariffs, international monetary agreements, international trade agreements, and so on, is because it is the fundamental economic laws that are perhaps of greatest importance to the electrical industry, and because they are so profoundly influencing the economic policy of industries generally.

During the past few years, for instance, we have seen in the basic industries the formation to an increasing extent of amalgamations, combines, and other forms of merging of interests. By the absorption into one unit of a number of individual producers, concentration in more efficient works, improved mechanization in production, and unified control, each basic industry is endeavouring to reduce manufacturing costs, increase output, and provide a greater opportunity to compete in both the home and the export market. At the same time its policy is creating industrial conditions which may adversely affect other industries and purchasers generally, cause unemployment, and reduce purchasing power. The question therefore arises whether, with similar conditions operating in other basic industries, consideration should not be given to a smoother transition from one stage of economic development to another. The serious derangement in the industrial and social life of the nation, due in considerable measure to the displacement and supersession of so many of the workers, demands priority of attention by the Government. Perhaps the establishment of the national grid, providing a completely flexible system of transmission of power in large or small quantities at an equitable economic price in all areas, may enable the electricity supply

industry to assist in the solution of this urgent national problem.

The economic policy of that industry in more recent years has been the provision of a full supply of electricity in all areas to every class of user, the judicious lowering of prices whenever possible, and the general improvement of its commodity as a public utility. The success which has attended its efforts, even during a period of prolonged depression, is shown by the figures that I have selected from the Electricity Commissioners' Return of Engineering and Financial Statistics, for the purpose of indicating the rate of national progress (see Table 1).

TABLE 1.

Year	Total consumers	Total kW connected	Total units sold
	millions	millions	millions
1928	2·599	8·969	7 003
1929	3·006	9·970	7 800
1930	3·471	11·124	8 666
1931	4·012	12·864	9 073
1932	4·646	14·319	9 501
Increase (1932 on 1928)	78·7 %	59·6 %	35·6 %

The relative increase in kW connected and units sold discloses the rather interesting fact that while there has been a steady increase in both, the ratio has not been maintained. That is to say, the curve of units sold has shown a tendency to fall away. This, I submit, is explained by the increasing disability, owing to financial stringency, to make use of the apparatus installed.

The electricity supply industry in Great Britain enjoys no such comfortable monopoly as is so frequently alleged, but has to engage in a ceaseless struggle for economic supremacy against its keenest competitor, the gas industry. The comparison shown in Table 2 of the rate of progress of the two industries for the five years ending 1932 (including the trade slump period from 1929) will probably be a matter of general interest.

TABLE 2.

Year	Electricity supply industry		Gas industry	
	Total consumers	Total units sold	Total consumers	Total gas sold
	millions	millions	millions	millions c. ft.
1928	2·599	7 003	8·901	282 430
1929	3·006	7 800	9·137	292 598
1930	3·471	8 666	9·343	289 991
1931	4·012	9 073	9·558	290 693
1932	4·646	9 501	9·773	286 988
Increase (1932 on 1928)	78·7 %	35·6 %	9·7 %	1·6 %

I propose now to pass on to other matters which in my opinion are more important to the electrical industry. It is clear that, in considering the interests of the industry as a whole, we cannot divorce manufacturing interests from supply interests. The favourable position attained by the electricity supply industry has been due in no small measure to the efficiency of the manufacturers, who have liberally supplied their expert technical knowledge in the development of all those things required by the electricity supply industry in the conduct of its business. Wholehearted co-operation between the manufacturing and the supply sections is clearly conducive to the efficiency of the electrical industry as a whole, and to the achievement of that purpose which will best serve our mutual interests, namely the production of electrical energy on a national basis at the lowest economic cost and the selling of that energy at the lowest economic price to the greatest possible number of users. It is in the interests of the supply section that the manufacturing section should be maintained in a thoroughly healthy condition, and that it should be able to secure a steady outlet and an economic price for its products. The exercising of any influence which tends to force down manufacturers' prices below a true economic level, under the mistaken impression that it is necessarily to the benefit of the supply section always to buy at the lowest price, may have a very definite repercussion upon the supply section. On the other hand, any attempt by manufacturers to maintain too high a price for their products must necessarily restrict the amount of business which can be done by the supply section, in that it increases the capital charges on account of generation, transmission, and distribution, and reduces the demand for consuming devices.

Economy in capital expenditure has an important bearing on the question of electricity costs, especially if we bear in mind that of the total costs involved in providing an electricity supply at the consumer's premises capital charges represent some 40 per cent. In arriving at this figure, which I have abstracted from the Electricity Commissioners' Return of Engineering and Financial Statistics, I have assumed that items of an exceptional nature do not affect the net total expenses, and that, in the absence of a closer analysis, depreciation and reserve provision by companies, and sinking-fund renewals and reserve contributions by public authorities, may be regarded as capital charges of parallel effect.

There is one direction in particular in which the manufacturing and the supply sections can influence the position and effect substantial capital savings to the electricity supply industry, and that is as the result of joint scientific and industrial research and standardization, particularly as represented by the British Electrical and Allied Industries Research Association and the British Standards Institution respectively.

The subject of manufacturers' prices is closely allied to the vexed question of trade discounts. This particular question has been discussed on many occasions and at great length, but, unfortunately, we appear to be getting no nearer to a happy solution. The prospect of mutual agreement is, I fear, rather remote unless the manufacturing and the supply sections can come to some

satisfactory understanding on the problem of distribution of the manufacturers' products and make possible selling conditions under which the retail price to the consumer is much more comparable with the selling price of the product packed ready for shipment at the manufacturer's works, due allowance being made for the cost of advertising and general publicity. It is not an impracticable proposal that authorized electricity undertakers individually or collectively should themselves become direct distributors of the manufacturers' products. A large number of undertakers, especially the more enterprising ones, already have available the financial and administrative machinery necessary to give effect to such a policy.

During the past few years the whole question of what constitutes "fair trading" has been the subject of acute controversy. A specially constituted committee known as Committee D was set up by the Electric Fittings Statutory Committee to explore the whole question, but, unfortunately, chiefly owing to the fact that its deliberations and recommendations were, in my opinion, more concerned with the preservation of the *status quo* of certain sections than with the real development of the electricity supply industry, it has achieved nothing of any practical value. It is abundantly clear that the supply industry could not associate itself with the proposals of Committee D, and it has adopted the only attitude possible, namely to decline to become a party to a policy which is inimical to its true interests and a hindrance to the fullest use of electricity by the consumer. By an energetic forward policy authorized electricity undertakers, both municipal and company, are at last securing a large-scale development of the use of domestic apparatus; and why should they be parties to any policy that could only have the effect of tying their hands and stultifying progress? The supply industry has fully justified its claim to the "most-favoured-nation" conditions in the matter of the purchase for resale of manufacturers' products.

Electrical contracting is another section of the electrical industry that merits a special reference in this Address. Through the unremitting efforts of those electrical contractors who are really efficient and progressive the output of authorized undertakers has been substantially increased and the adverse effect of the industrial depression materially lessened. It is hardly necessary to say, therefore, that it is clearly in the interests of authorized undertakers in every part of the country to co-operate in every possible way with efficient and progressive electrical contractors. At the same time it is imperative that in accordance with Section 48 of the Electricity (Supply) Act, 1926, all authorized undertakers should exercise their trading powers to the fullest extent, and that co-operation between undertakers and contractors should be collateral. If it is not, and any serious attempt is made to restrict the exercising by authorized undertakers of their rightful powers, I can visualize that it will only be a matter of time before conditions similar to those in the gas industry will also obtain in the electricity supply industry, so far as the provision of electric fittings and all that is embraced in that broad definition of Section 48, "Sale of Fittings," is concerned.

I propose now to discuss those economic considerations which more particularly concern the supply section of the industry.

The future policy of the electricity supply industry will be determined largely by the policy of the Central Electricity Board, whose powers are of course defined by the Electricity (Supply) Act, 1926, and whose economic policy, as inferred from the Act, is to secure the greatest possible efficiency in the production of electricity with a view to the gradual lowering of price, the increasing of demand, and the provision of an abundant supply throughout the country.

The Board has now practically completed the construction of the grid, which to a limited extent has already commenced operation, and one is disposed to the view that no new industrial organization could have come into being under more discouraging industrial conditions. At the same time, the adverse conditions have been of some help, for the Board has had the advantage of purchasing its requirements at a time when minimum prices have been ruling, and the retardation of development has given the necessary breathing space to enable the construction of the grid to proceed to completion without placing too great a strain upon the capacity of many existing individual plants to meet immediate demands.

In the interests of economy the generation of electricity under the Board's administration will be confined to the comparatively limited number of selected stations; and the Board operating by means of the grid through the selected stations will, like every other large-scale industrial organization, produce its commodity under the most economic conditions possible, putting its capital to the best use and concentrating production in those selected stations of the highest efficiency.

The Board, however, unlike other large-scale industrial organizations, is not permitted to concentrate production in the most efficient works without regard to the cost of production in the less efficient works.

In order to ensure a general reduction in price and an increased demand, it is very desirable that all authorized undertakers should receive a reasonable share of the economic benefits to be obtained from the national scheme. For instance, in the operation of the scheme it may be shown to be justifiable that certain selected stations should, in the interests of the area in which they are generating, curtail their output as a result of concentration of production in the more efficient base-load stations; and in consequence the savings resulting from this concentrated production in the base-load stations may be unequally distributed among the producing stations as a whole. It would therefore appear reasonable to suggest that the savings should be proportionately distributed among all the generating stations, or at least among all those in each respective area. This particular consideration is, I believe, already engaging the attention of some of those responsible for the generation of electricity under the national scheme, and no doubt it will receive the full and sympathetic consideration of the Board. A satisfactory solution of this question would undoubtedly simplify negotiations between the Board and individual authorized undertakers.

The fixed objective of the Board is to increase the demand and to load the grid, and the disparity in the

efficiencies of the stations administered by the various authorized undertakers appears to be evidence that much may be effected towards the attainment of the Board's objective through the taking of economic action by the authorized undertakers themselves, for the taking of such action will of necessity tend towards reducing the price and increasing the demand.

As a means to ascertaining the direction in which economic action is possible, the statistics prepared by the authorized undertakers could be reviewed, simplified, and perhaps supplemented, to ensure that vital economic facts, particularly those as to input and output, are quickly disclosed. The taking of most important economic action may be delayed for years, to the detriment of both undertakers and consumers, because of the concealment of vital economic facts by unsuitable statistics. To allow the administrative and executive staffs of authorized undertakers to have a greater financial interest in the affairs of the undertakings, such as by the subscription of capital on specially convenient terms, by the payment to the staffs of adequate salaries commensurate with their responsibilities, and perhaps by the payment of a special bonus on results, would undoubtedly be an added incentive to the taking of that economic action upon which the success of the undertakings principally depends.

I have confined myself so far mainly to economic considerations as they affect the electricity supply industry on the generation side, but we know that in future the majority of engineers will be concerned almost exclusively with the economic considerations underlying the distribution of electricity. I shall therefore, in conclusion, direct attention to that important subject.

As we know, the jurisdiction of the Board is limited to generation and does not extend to distribution. There is, however, as between the various authorized undertakers the same disparity in the efficiency of distribution as in the efficiency of generation, but distribution has not yet received the same legislative treatment as generation. As a result, economies that could be effected in distribution are not yet attainable because a really national economic policy has not so far been conceived. We cannot imagine one of the large basic industries divorcing the selling from the producing side of its organization, but rather would it insist upon a co-ordinated system under one complete and supreme control in order to ensure the best economic results. Why should it be supposed that the electricity supply industry can attain its full development without a similar co-ordination? It cannot.

We have recently heard a great deal about the lack of what, for want of a better name, is called distribution efficiency, and I should here like to express my appreciation of the clear and scientific manner in which Mr. J. M. Kennedy and Miss Noakes dealt with the subject in their recent paper.* At the same time I disagree with some of their contentions and deductions, although not with their ultimate recommendations, and the discussions on the subject force me to the conclusion that much of what was envisaged is not borne out by a critical examination of existing conditions. In fact in the case of many authorized undertakers, particularly local-authority undertakers, there is a great measure of distribution efficiency; and where there is not as yet so clear an indication of it this is frequently due, not to lack of enterprise, but in the main to the industrial depression and to circumstances over which the authorized undertakers have no control. In support of this I would refer to a feature of recent progress mentioned earlier in this Address, namely, that whilst the curve of kW connected shows a steady upward and even increasingly steep tendency, the curve of units sold is not at the present time following the same line, but is falling away. The maintenance of the rate of progress in kW connected is indicative of activity in the securing of business constituting a potential demand rather than an actual demand, and I submit that this is at least in part an answer to the absence of improvement in distribution efficiency expressed in terms of capital expenditure to which such prominent reference was made in the above paper. At the same time it must be admitted that there is a great deal which strengthens the contention that much requires to be done to improve selling conditions.

In June, 1931, in a paper which I read before the I.M.E.A. entitled "The Future Development of Electricity Distribution in Great Britain," I pointed out that the average gross saving in generating costs as a result of the national scheme of generation would only be of the order of 0·0554d. per unit sold, and that to secure further economies it would be necessary to effect a reduction in the average cost of distribution. I dealt fully in the paper with the many directions in which, more particularly, the economic reorganization of distribution could be effected, and with the various obstacles to be surmounted for the proper development of the electricity supply industry. The aim of the industry is to secure the maximum demand for electricity and to sell it at the minimum economic price; but it may not be conducive to the proper development of the industry to sell even a proportion of its output at a price below the true economic level simply for the purpose of loading the grid, for whilst to do so may increase the demand, it may well be that one class of consumer is obtaining an undue benefit at the expense of other classes. The interests of the industry are best served by selling its output at a true economic price to all classes of consumers, with the judicious lowering of prices upon a sound and equitable basis as the national demand increases.

In order to obtain the economies and surmount the obstacles dealt with in that paper, and to assist in the advancement of the electricity supply industry towards an impregnable position against its competitors, I submitted what, perhaps, at that time were regarded by many as unorthodox if not heretical views and as an incitement to the introduction of legislation that would place the industry upon a quasi-national basis. Not a few, I fear, regarded my views as the advocacy of pure collectivism. Those who regarded them in this light, however, must surely have done so either by reading into them much that was not intended or by failure to perceive the modern trend of economic development. During the past two years we have received conclusive evidence as to the direction in which the major industries and public utilities are moving. We have the examples of the London Passenger Transport Board, the Milk

* *Journal I.E.E.*, 1933, vol. 73, p. 97.

Marketing Board, the Bacon Marketing Board, the steel merger, and the recently proposed Lancashire Transport Board. We also see the same trend of economic development in other spheres of our national life, and in the U.S.A.—at least to a limited extent—an attempt at the State control of industry. Is it possible, therefore, that a great industry like the electricity supply industry can continue with impunity under present conditions, at the same time fulfilling its true function as a public utility service and taking its full share of responsibility in a return to lasting national prosperity? I submit that it is not possible.

That this is the position is surely, if slowly, becoming the settled conviction of those primarily responsible for the development of the electricity supply industry, and the sooner there is provided a scheme of re-organization on broad and statesmanlike lines, the sooner will this great industry be given the opportunity to render that full and complete service demanded of it. It must be a scheme which, while retaining a full measure of public control, will provide an administrative organization of technical and commercial experts whose major consideration will be a system of economic development such as I have advocated in the past and have emphasized in this Address, namely, a completely co-ordinated national electricity scheme. In its establishment the heritage of political and financial vested interests and those of speculative shareholders, or requirements of a purely individualistic or parochial character, must not be allowed to prejudice the full economic development of the electricity supply industry. It must, for instance, in the case of local-authority undertakings, be made impossible for this great public-utility service operating as a trading undertaking to be fettered and restricted by too insistent a demand for compliance with the administrative procedure governing non-trading services, on the grounds of the specious argument that being one section of the corporate body it must be governed and regulated by the same system as applies to the other sections of the public service; nor, where both utilities happen to be under one particular local-authority control, should it be possible to subject the electricity undertaking to retardation and limitation in order to bolster up the interests of its greatest competitor. Rather in such cases should there be a policy of collateral development, either industry being permitted to provide the maximum public service in accordance with the predilection of the consumer. On the other hand, I suggest that no scheme would be acceptable which made possible in the electricity supply industry the development of control by so-called public-utility trusts, whose economic policy may be unduly influenced by considerations of financial groups of not only British but also foreign nationality who are in the industry mainly for personal monetary gain without necessarily the fullest regard to the best interests of the public service.

To-day there is at least some reason for taking an encouraging view, for although we know that rumour is said to be a lying jade, we have also in mind the proverb that "Straws show which way the wind is blowing."

THE INTERFERENCE OF ELECTRICAL PLANT WITH THE RECEPTION OF RADIO BROADCASTING.

By A. MORRIS, Member.

(*Introductory remarks to a discussion before the* WIRELESS SECTION, *22nd November*, 1933.)

INTRODUCTION.

In the engineering development of radio broadcasting services an outstanding difficulty on the reception side has been that of electrical interference. The following notes deal with the interference arising from the operation of electrical machinery.

GENERAL FEATURES CONCERNING INTERFERENCE FROM ELECTRICAL PLANT.

Any item of electrical plant in which the operating current is suddenly varied or interrupted, either intentionally or as a feature of its functioning, will sustain a change of potential of one portion of the circuit with respect to another portion, or with respect to earth. In such circumstances an additional or parasitic electric current will flow in the system. A large number of items of electrical plant appear to produce such an effect even when satisfactorily performing the work for which they are designed.

Such currents give rise to interference with radio reception by producing audible noise at the loud-speaker or headphones in the case of a sound transmission, or by mutilation of the picture in the case of television. The interference may be general over the whole of the broadcasting wave-band, or alternatively it may be much more pronounced over one portion than over another. The characteristic sounds produced by a number of items of plant* have been recorded by the Gramophone Co., in co-operation with the Post Office Engineering Department, for servicing purposes.

RADIATED AND CONDUCTED TYPES OF INTERFERENCE.

Interfering currents arising in the manner outlined above are capable of widespread propagation. The type of interference known as "radiated interference" may either be directly radiated from the source or reach the receiver as mains-borne radiation. The interfering range of the mains-borne component is in general much greater than that of the directly radiated component.

In certain cases interfering currents are transmitted along the supply mains and fed into the radio receiver along with its normal power supply. The resulting disturbance is known as "conducted interference." Such interference is seldom severe in a modern receiver when arising from the passage of currents of radio frequency.

AURAL SIGNAL/NOISE RATIO.

In any communication system the degree of freedom from interference depends upon the relative strengths of the desired signal and of the disturbance. This signal/noise ratio is of fundamental importance in all communication systems, including broadcasting systems.

The Technical Secretariat of the I.E.E. Committee on Electrical Interference with Broadcasting has had a gramophone record prepared for the purpose of demonstrating aurally the effect of various values of signal/noise ratio ranging from zero to + 40 decibels. The record was made by the Gramophone Co. and is the property of the British Broadcasting Corporation. Different types of programmes were used in its preparation, together with various interfering sounds such as steady notes at different frequencies as well as the noises common to communication systems. Opinion based upon this record appears to indicate that for concert material, subject to continuous noise, a signal/noise ratio of + 40 decibels is necessary for the purpose of ensuring high-quality reception.

RADIO SIGNAL AND INTERFERENCE LEVELS.

With the present international restrictions in regard to the power of medium-wave and long-wave transmitters, and owing to the increasing use of ultra-short waves of low power, the actual level of the radio interference from electrical plant is required to be relatively low in order to ensure services with a satisfactory aural signal/noise ratio.

TABLE 1.

Lower Limit of Useful Signal Field for Broadcasting Services on Various Wave Ranges.

Wave range	Lower limit of useful signal field
Below 20 m	10 μV per metre ($\equiv$ + 20 decibels on 1 μV per metre)
20 to 200 m	20 μV per metre ($\equiv$ + 26 decibels on 1 μV per metre)
200 to 2 000 m	1 mV per metre ($\equiv$ + 60 decibels on 1 μV per metre)

The figures contained in Table 1 may be regarded as representing the lower limit of useful signal field for broadcasting services on various wave ranges. When read in conjunction with a suitable value for signal/noise ratio, they convey a quantitative idea of the degree to which it is desirable that the general level of radio noise from electrical plant should be controlled.

The actual level of the noise in any particular locality is usually rather difficult to measure, especially in situations close to interfering sources. As an actual example of the level of interference from a particular item of plant, however, and in order to supplement

* The interfering noises from a number of items of electrical plant were demonstrated at the meeting—aurally by means of a radio receiver, and visually by means of a cathode-ray oscillograph.

the use of Table 1, the results of measurements made at a distance of 15 yards from a 132-kV transmission line

TABLE 2.

Magnitude of the Measured Level of Interference at 15 yards from a 132-kV Transmission Line.

Wavelength	Interference level, in decibels on 1 μV per metre	
	Dry condition	Wet condition
15 m	− 16	+ 2
20 m	− 12	+ 8
200 m	+ 16	+ 42
2 000 m	+ 30	+ 58

on dry and wet days respectively are reproduced in Table 2.

COMMERCIAL CLASSIFICATION OF INTERFERING ITEMS OF PLANT.

For convenience in dealing commercially with electrical plant, from the radio-interference point of view, the items have been classified as:—

A (i). Domestic apparatus.
  (ii). Small commercial apparatus.
B. Large commercial plant.
C. Traction apparatus.
D. Automobiles and aircraft.

The items included in each of the above classes are set out in Appendix 1.

PARTICULARS OF THE INTERFERENCE FROM THE PRINCIPAL TYPES OF PLANT.

Experience to date of this aspect of the subject is summarized in Appendix 2. It will be seen that all the items referred to give rise to direct and mains-borne radiation, except of course the spark-ignition systems of automobiles and aircraft, from which the radiation is wholly direct. Furthermore, the interference from such systems is usually confined to short-wave and ultra-short-wave services.

METHODS OF ENSURING FREEDOM FROM ELECTRICAL INTERFERENCE.

(*a*) *Suppression at the source.*

In the case of definitely interfering types of plant, freedom may be obtained by the application of suppressive measures to such plant, whereby the parasitic currents are restricted in such a manner as to prevent their propagation from the source, either as direct or as mains-borne radiation. The suppression devices required for this purpose may be embodied in the plant during its design and manufacture, thus ensuring the equivalent of a non-interfering type. Alternatively, the suppressors may be added subsequent to installation and initial operation of the plant.

The advantage of suppression at the source lies in the immunity thereby conferred upon all radio receivers within, or liable in the future to come within, the disturbing range of such source.

In those instances where the disturbing currents reach the radio receiver by radiation to, and pick-up on, the aerial system, and where practicable modifications of this system are without effect upon the signal/noise ratio of the receiving system, suppression at the source is the only cure. Electric traction systems, of which the trolley-bus is a notable example, as well as the spark-ignition systems of automobiles and aircraft, fall within this category.

(*b*) *Ameliorative measures at the radio receiving station or at the radio receiver.*

Failing action at the source, ameliorative measures may in certain instances be taken at the receiving station or at individual radio receivers.

PRINCIPLES UNDERLYING THE DESIGN OF SUPPRESSORS AND OF OTHER AMELIORATIVE DEVICES.

(*a*) *Suppression at the source.*

The methods involve the use of resistances or of choke coils for reducing the magnitude of the currents, and of earthed condensers for by-passing them to earth. These items are required to be used sometimes separately, and at other times in combination. Electrical screening is sometimes also necessary, but when employed it should be as complete as possible.

Appendix 3 gives technical particulars of various suppression devices. Figs. 1 to 12 show their circuit arrangement.

(*b*) *Ameliorative measures at the radio receiving station or at the radio receiver.*

Such ameliorative measures as may be taken at the receiving station or at the receiver are of necessity limited to the control of all interference other than that which is actually picked up by the aerial. In this connection the term "aerial" is to be understood to exclude the transmission system which connects it to the radio receiver.

Choke coils and earthed condensers inserted in the incoming power supply and located at or near to the main switch of the receiving station will considerably restrict the flow of disturbing radio currents in the internal wiring of the premises, thus limiting local radiation and thereby interference pick-up by the aerial as well as the magnitude of the currents directly conducted to the receiver via its power supply. Such devices are referred to as mains filters. If, in addition, the internal wiring of the premises is enclosed in efficiently earthed conduit, the radiation effect of any residual currents carried by such wiring will be reduced.

The elevation of the aerial and the use of a screened lead-in is beneficial when the aerial can be elevated to an extent which will place it outside the effective range of intense local radiation. Special screening methods, involving tuned impedance-matching circuits in conjunction with single- or double-wire transmission lines, are desirable in this case in order to minimize loss of signal strength. In those cases where the loss of signal strength, consequent upon the use of such methods, necessitates the operation of the receiver at relatively

high sensitivity, the accompanying increase of receiver background noise may prove disadvantageous.

Even with screened receivers and specially-designed transmission lines, elimination cannot be effected unless the aerial can be placed outside the field of interference. The application of these means is, however, of special facturing cost of from 5s. to £2 per coil would apply to 600-microhenry chokes, suitable for currents of from 5 to 50 amperes respectively. Available figures indicate that for the suppression of the audio-frequency harmonics, up to and including the 24th, of mercury-arc rectifier systems, the retail price per kW is from 6s. to

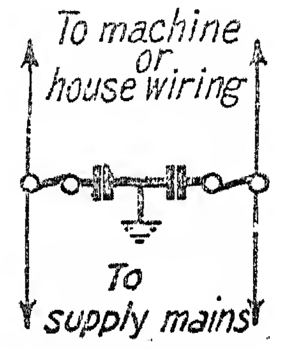

Fig. 1.

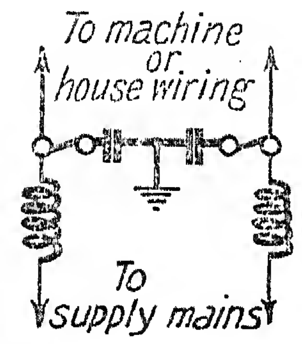

Fig. 2.

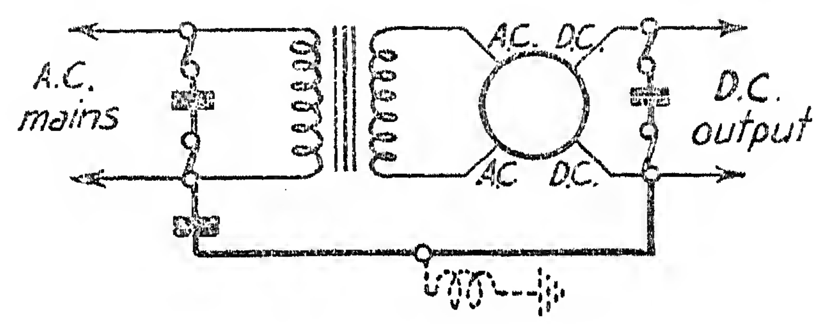

Fig. 3.

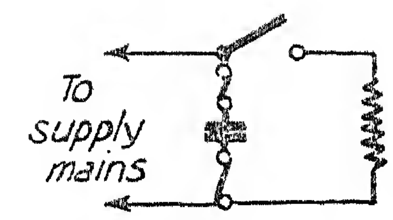

Fig. 4.

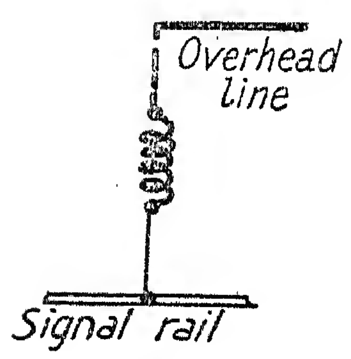

Fig. 5.

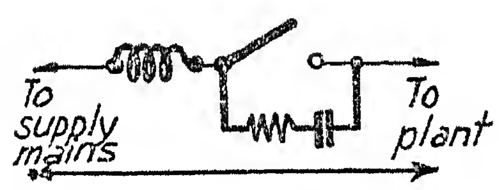

Fig. 6.

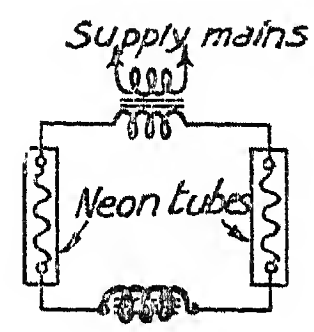

Fig. 7.

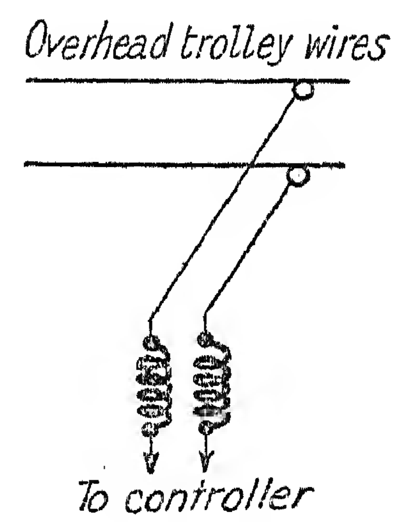

Fig. 8.

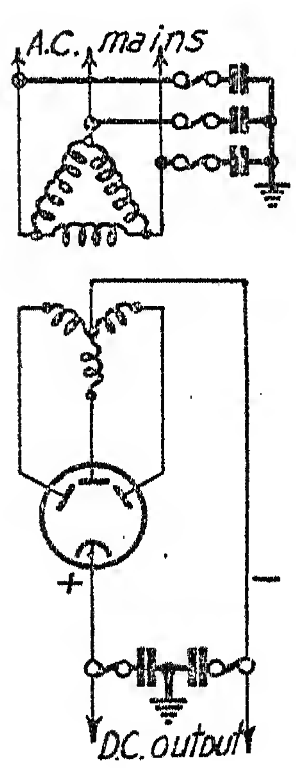

Fig. 9.

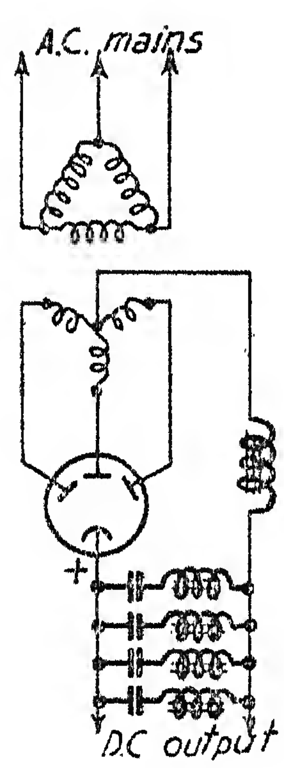

Fig. 10.

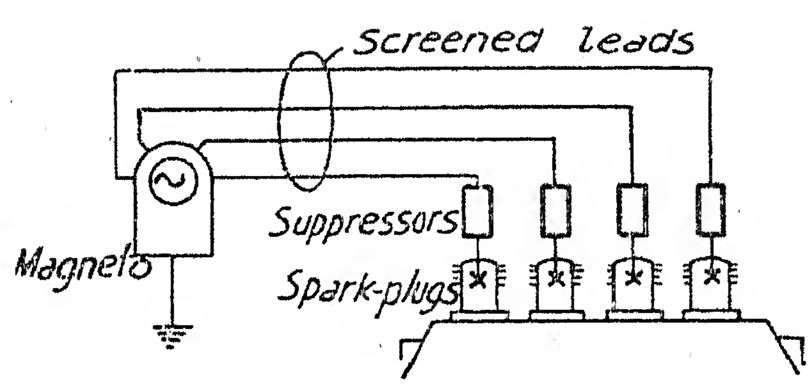

Fig. 11.

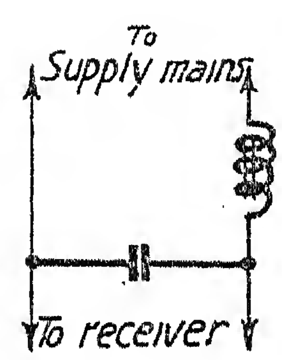

Fig. 12.

value in some cases, especially where the cost of their elaboration is justified.

Cost of Interference Suppressors.

The cost of incorporating suppressors during the manufacturing stage, in the various items of domestic and small commercial plant (see Appendix 1, Sections 1 and 2), has been approximately computed. The costs are such as to increase the retail price of the item by from 1 to 8 shillings. In a few instances re-design of the items would be beneficial from the point of view of simplification of the suppressor and of its housing.

In regard to large commercial plant (see Appendix 1, Section 3), the cost will be governed considerably by the cost of the choke coils, in those cases where such chokes constitute the basis of the suppressor. A manu-

5s. for rectifiers of from 1 000 kW to 2 500 kW output respectively.

So far as traction systems are concerned (see Appendix 1, Section 4), a pair of choke coils suitable for trolley-bus systems, in which the starting current is of the order of 300 amperes, costs from £12 to £16.

Suppressors for the ignition systems of automobiles and aircraft are not yet in general use, neither is the demand very great. The present-day price of such suppressors and of complete screening systems is probably much higher than it will be in the future.

General Position in Regard to Radio Interference.

Electrical interference with broadcasting has been experienced in all countries which have shared in the

scientific and commercial development of electrotechnics, and particularly in those countries where electricity has been extensively applied for domestic and industrial purposes.

The Wireless Telegraphy Acts of this country do not deal with the matter of electrical interference, and the electrical operating companies and other owners of electrical plant are accordingly in a position to repudiate liability for disturbance to broadcast reception. A similar position has existed in a number of other countries. The present tendency, however, is in the direction of placing responsibility for the avoidance of interference upon the user of electrical plant, and various laws and decrees have been enacted in certain countries in order to secure this object.

The subject of electrical interference has also been considered at conferences of the International Telegraphic Union and of the International Electrotechnical Commission. Each of these bodies has recommended that steps be taken to render electrical plant free from the susceptibility of causing interference.

In this country the Institution has set up a committee* to study the matter and to make recommendations to the Council.

Assistance Afforded to Broadcast Licensees in This Country.

Although the Postmaster-General has no statutory power under which he could compel owners to suppress interference from electrical plant, the Post Office undertakes to assist the public in the elimination of electrical interference with broadcasting. The British Broadcasting Corporation fully co-operates in this matter. Complainants of electrical interference with broadcasting are furnished by the Post Office with a questionnaire, which, when completed, provides full information for the subsequent investigation of the complaint. A copy of this questionnaire will be found in Appendix 4. It is available on request at all post offices throughout the country. All complaints of interference received from licensees, either directly or via the B.B.C., are investigated by the Post Office Engineering Department and the interference is traced to its source. On receipt of permission from the owners of interfering plant, a cure is demonstrated and particulars furnished as to the method of fitting the appropriate suppression device. Difficulties are sometimes met with in regard to the adoption of the cure. One main and usual difficulty is that of incidence of the cost. The owners are first approached on this matter, but, at times, it is necessary to attempt settlement on the basis of a contribution from all the parties concerned, or from the complainants only. Numbers of interference cases are satisfactorily completed, but numbers remain unsettled because of the inability to reach agreement on this matter.

Conclusion.

Experience indicates that the amount of radio interference is becoming greater and its distribution more widespread. There is believed to be a large body of persons which, for one reason or another, has not yet registered its dissatisfaction. There are districts in which electrical interference has existed for many years; many licensees in such districts have no knowledge of the possibilities of suppression, whilst numbers of other persons refrain from becoming licensees on account of the prevailing conditions.

As has already been pointed out, the radio engineer can ameliorate particular interference conditions at the radio receiving-site, but the general level at any particular locality of interference from electrical machinery can be controlled only at the source. This control, which is in the hands of those responsible for the plant, presents no outstanding difficulty, since the fundamental technique of this subject, as indicated above, is relatively simple. The present-day problem of electrical interference is in fact not primarily an electrical one, but consists of the reconciliation of the economic aspects of the various interests.

* See *Journal I.E.E.*, 1933, vol. 73, p. 93.

APPENDIX 1.

Commercial Classification of Interfering Items of Plant.

(1) *Class A* (i). *Domestic apparatus.*

Fans; vacuum cleaners; refrigerators; sewing machines; washing machines; floor polishers; hair driers; heating pads; electric bells; electric clocks (contactor type); high-frequency medical apparatus ("violet ray"); electric wiring; vibrators (body and face); water heaters (thermostatically controlled).

(2) *Class* A (ii). *Small commercial apparatus.*

Refrigerators; dough mixers; ice-cream machines; sausage machines; coffee grinders; dental drills; hair driers and clippers; paint sprayers; cash registers; calculating machines; incubators (egg and bacteriological); vibrators (body and face); cream or oil separators; petrol pumps.

(3) *Class* B. *Large commercial plant.*

Motors; generators; rotary rectifiers; flashing signs (motor-driven and contactor type); traffic signals (motor-driven and contactor type); lift motors and contactors; oil-burner motors; thermostatic signs; vibrating-reed rectifiers; telephone switching apparatus; incubators (10 000-egg); static rectifiers (mercury-arc or valve); neon signs; diathermy apparatus; ultra-violet-ray lamps; dust precipitators; overhead high-tension transmission lines.

(4) *Class* C. *Traction plant.*

Trams; trolley-buses; electric railways; railway signalling systems.

(5) *Class* D. *Automobiles and aircraft.*

Petrol engines with coil and/or magneto ignition.

APPENDIX 2.

Particulars of the Interference from Various Types of Electrical Plant.

Type of interfering electrical plant	Type, and range, of the interference	Remarks
(*a*) Motors of both d.c. and a.c. types	Is chiefly of the radiated type, though much of it is mains-borne. Is usually inappreciable beyond a range of 200 yards.	Includes small totally-enclosed motors for domestic use as well as the larger commercial types of motors. Alternating-current induction motors in general give little interference.
(*b*) Generators of both d.c. and a.c. types	May be of the radiated and directly-conducted (audio-frequency) types. Much of the radiation is mains-borne. Is usually inappreciable beyond a range of 200 yards.	Includes rotary convertors. Commutator sparking is not an essential feature of interference from motors and generators.
(*c*) Rectifiers of the commutator type	Consists principally of direct radiation from the plant, including the batteries undergoing charge. Is very severe up to a range of 200 yards. The mains-borne radiation is small in comparison with the direct radiation.	Used for battery charging and for cinema arcs.
(*d*) Vibrating-reed rectifiers; flashing signs of various kinds, including road and railway control signals; telephone switching plant; electric bells, ovens, heating pads, and other forms of thermostatically-controlled plant; also electric tramway and lift controllers	Consists principally of mains-borne radiation. Has a range up to 100 yards.	
(*e*) Neon signs	Is of the radiated type, both direct and mains-borne. Has a range of about 200 yards in the high-frequency type of sign and about 50 yards in the low-frequency type.	Includes the high-frequency (indoor) type as well as the more common low-frequency (outdoor) type.
(*f*) Lift plant	Is of the radiated and directly-conducted types. The influence of the direct radiation extends up to about 25 yards.	Includes the motor and controller and trailing cables. Lift motors of the d.c. type generally cause more severe interference than those of the a.c. type.
(*g*) Tramway and trolley-bus systems	Is of the radiated type. Much of it is radiated from the overhead feeders. Is widespread in regard to range.	Includes the traction and compressor motors, the controller, and the collectors and overhead feeders.
(*h*) Mercury arcs	Is mainly of the directly-conducted (audio-frequency) type, but is accompanied by the radiated type. Is widespread in range in the case of sub-station plant.	Includes the types used at rectifier substations on d.c. supply systems, as well as the smaller types used for operating d.c. plant (such as lifts and cinema arcs) from a.c. mains.
(*j*) High-tension overhead transmission systems	Is of the radiated type. In addition to interference with broadcasting, interference with short-wave radio services has arisen from this source. Range is dependent upon the nature and extent of the discharge.	Such systems cause interference chiefly by corona discharge at insulators.
(*k*) Spark ignition-systems	Is of the directly-radiated type. Interference only with short and ultra-short waves.	Relates to types incorporated in motor-car and aeroplane engines.
(*m*) High-frequency medical apparatus	Is of the radiated type. The direct radiation is intense. The mains-borne radiation extends over a range of about 300 yards.	This class of apparatus normally operates much in the same way as a spark radio transmitter.

APPENDIX 3.

Technical Particulars of Various Suppression Devices.

Suppression devices			Type of interfering plant for which suitable	Remarks
Location	Circuit diagram	Description		
At source	Fig. 1	2 × 2 μF or 2 × 4 μF	Motors and generators of both d.c. and a.c. types	Condensers are mounted in metal case complete with terminals and fuses.
At source	Fig. 2	2 × 4 μF or 2 × 2 μF; 2 × 600 μH	Motors and generators of both d.c. and a.c. types	
At source	Fig. 3	2 × 2 μF; 1 × 4 μF; 1 × 600 μH	Rectifiers of the commutator type	Choke required when earthing of system is necessary.
At source	Fig. 4	2 μF or 4 μF	Contacts of flashing signs of various kinds, including road and railway control signals, electric bells, ovens, telephone switching plant, heating pads and other forms of thermostatically-controlled plant; also electric tramway and lift controllers	It is essential that the condenser should be inserted as near as possible to the contacts and on the mains side of them.
At source	Fig. 5	600 μH	Railway control signal (GreatWestern type)	The engine picks up a pulse when approaching signal box. Choke inserted in case, complete with insulating compound for outdoor fitting.
At source	Fig. 6	Choke 600 μH; condenser 0·1–2·0 μF; resistance 50–100 ohms	Flashing-sign contacts, electric tramways and lift controllers	Choke not always essential, but if fitted should be placed immediately preceding contacts.
At source	Fig. 2	2 × 2 μF or 2 × 4 μF; 2 × 600 μH	Vibrating - reed rectifiers	
At source	Fig. 7	Iron-core choke 50 H (at 50–100 mA)	Neon signs	If and where possible the cables from each end of sign to the transformer to be of the same length. Choke to be insulated for working voltage of 10 kV to earth, and preferably sectionally-wound.
At source	Fig. 2	2 × 4 μF; 2 × 600 μH to carry 50 amps.	Lift plant	Satisfactory suppression of interference from most types of lifts is secured by this means.

APPENDIX 3 (*continued*).

Suppression devices			Type of interfering plant for which suitable	Remarks
Location	Circuit diagram	Description		
At source	Fig. 8	2 × 600-μH choke coils	Tramway and trolley-bus systems	The device consists, in the case of trolley-buses, of two choke coils mounted in metal cases and inserted one in each line at the base of the trolley arm. A single coil is required in the case of tramways, supplemented at times by a condenser.
At source	Fig. 9	All condensers 2 μF	Mercury-arc rectifiers (high-frequency interference)	In the case of small rectifiers such as cinema equipments (low-voltage a.c. supply) this method has proved satisfactory.
At source	Fig. 10	Audio-frequency filter circuit	Mercury-arc rectifiers (low-frequency interference)	
At source	Fig. 11	Screened wiring and special suppressors at spark plug	Spark ignition system	Screening of the magneto will be necessary for complete suppression.
At source			High - frequency medical apparatus	Screening of the room in which apparatus is installed is necessary for complete suppression.
At source			Extra-high-tension transmission systems	The insulators should be of such a type as to limit corona and spark discharge to a minimum.
At listener's premises	Fig. 2	Mains filter: 2 × 4 μF or 2 × 2 μF; 2 × 600 μH	All plant which gives rise to mains-borne effects	Prevents high-frequency current from entering listener's premises via mains, but does not prevent radiation from neighbouring premises. This filter, in conjunction with screened lead-in at listener's set, will suppress locally-radiated interference.
At listener's premises	Fig. 1	2 × 2 μF	Mercury-arc (high-frequency interference)	Condensers supplied complete in case with fuses for insertion at incoming mains to listener's premises.
At radio receiver	Fig. 12	Additional smoothing to receiver if operated from d.c. mains; 2-H choke, 4-μF condenser	Mercury-arc (low-frequency interference)	Suppresses low-frequency interference. May either be incorporated in the receiver or made up as a separate unit.

APPENDIX 4.

Electrical Interference Questionnaire Issued by the British Post Office.

If interference is experienced when stations of the British Broadcasting Corporation are being received and it has been ascertained that the receiving set is in no way faulty this form should be completed and forwarded by post.

The interference will be investigated and particulars of the necessary suppression apparatus will be furnished without charge. The costs subsequently involved in the permanent installation of suppression apparatus cannot be borne by the Post Office.

1. Are you using a valve set or a crystal set? If valve, state number of H.F. and L.F.
2. Does your receiver draw any part of its H.T. or L.T. supply from the electric light mains?
3. Has your set or aerial, etc., been altered in any way prior to the commencement of the interference? (Please give particulars.)
4. (*a*) Are your neighbours simultaneously suffering the same interference as yourself?
   (*b*) Is the proportion of interference to music the same in neighbours' receivers as in your own?
   (*c*) To which British Broadcasting Station do you listen most frequently?
   (*d*) Is this Station affected by the interference?
   (*e*) Is the Daventry Long-Wave Station (5XX) affected?
5. Do you know, and can you give the address of, any local listener who hears the interference at a greater strength (in proportion to the broadcast transmission) than yourself?
6. (*a*) Does the interference cease when you disconnect (1) your aerial, (2) your earth, or (3) both? (Please ensure that your set is not oscillating when the aerial or earth is removed.)
   (*b*) Have you examined your aerial and earth wires and connections for frayed strands or bad joints?
7. State periods when interference is most pronounced.
8. If you are not a new listener, has the interference suddenly commenced?
9. Can you give date when interference first noticed?

APPENDIX 5.

Brief Description of Field-Strength Measuring Set.

The set consists of a double detection receiver having an intermediate frequency of 300 kilocycles per sec. and using anode modulation on the first detector. The band width of the intermediate-frequency amplifier is about 10 kilocycles. Both detectors contain microammeters in their anode circuits. The first detector is calibrated as a valve voltmeter. The output of the second detector is kept constant by means of an attenuator in front of the intermediate-frequency amplifier. The signal is normally received on a frame aerial, the first detector valve being connected across one half of the frame, while a balancing condenser is connected across the other half of the frame, the centre point of the frame being earthed. A powerful local-signal oscillator induces a measurable voltage in a small coil which can be connected either in series with the frame or directly between the grid and filament of the first detector. The ratio between the voltage measurements on the first detector under these conditions determines the step-up due to the frame. With the coil in series with the frame the attenuator is adjusted to give a convenient output on the second detector. The signal oscillator is then switched off, the signal to be measured is tuned in, and the attenuator is adjusted to give the same output as before. From these attenuator readings and the dimensions of the frame the field strength can be readily computed. A vertical aerial can be used in place of the frame aerial. In this case calibration of the vertical aerial is effected by measuring, with both frame and vertical, the signal from an oscillator placed a short distance away. The limitation of measuring sets having the attenuator between the oscillator and the receiver, due to the difficulty in eliminating direct throw-in from the oscillator to the receiver, does not arise in the set described; elaborate screening of the local signal oscillator is accordingly unnecessary.

The equivalent field strength of the disturbance from an item of electrical plant can very readily be measured by the apparatus described above, the radio noise field being treated in exactly the same manner as an ordinary carrier.

Discussion before the Wireless Section, 22nd November, 1933.

Mr. J. M. Donaldson: The electric supplier is concerned with this subject in two ways. In the first place he may be an originator of interference—purely, that is, as a producer. It must be borne in mind, however, that a supply business does not really end when energy has been generated and has been transmitted to the user's premises and a meter installed. The supply undertaker goes farther than that; he is interested in the general use as freely as possible of all current-consuming apparatus. He is therefore just as much concerned as the contractor, manufacturer, and supplier, in seeing that the apparatus which is supplied is as cheap, simple, and little liable to go wrong as is possible. Those of us who, in recent years, have had to change systems over from direct current to alternating current have had these points very strongly impressed on us by bitter experience. Nearly everybody whom the supply engineer has to change over has an expensive wireless set which he values highly, and if he loses its use only for an evening he complains! Again, we in the supply industry used sometimes to feel a little annoyed with people who had wireless apparatus, because they did not appear to use much current. As far as that is concerned, however, things have moved rapidly, and at the present time many sets take as much as 60 to 100 watts. Moreover, a wireless enthusiast keeps his set on for a long time, and therefore may be using a good deal more electricity for lighting

than he otherwise would. I should therefore like to say to the supply industry that, although wireless enthusiasts may be something of a nuisance at times, it looks as if they are going to be good consumers. There is not much guilt attached to the supply industry now in the matter of causing interference. The ordinary rotary convertor which is used is not an offender, but I know that the mercury convertor is bad. The supply engineer must take the larger view that he is out to give service of every electrical kind. We had a mercury rectifier in our district; it was a very old one, the second to be imported into this country. When it began life in a new sphere it caused a great deal of trouble to wireless sets. Eventually this was very much alleviated on an individual set by the Post Office engineers, who fitted a large number of coils, condensers, and so on; these certainly looked more like the product of the laboratory than of the workshop. Eventually correcting devices were installed at the substation. Broadly speaking, the electrical supplier should take the attitude that he does not want to produce trouble of this kind, though I do not think in the present state of the art it can be stopped altogether. The attitude which the supplier might be expected to adopt would be that of saying "These people are second-comers; let them effect their own cure." I have been told, however, that this cannot be done, although only the other day I saw the advertisement of a reputable firm guaranteeing entire freedom from all interferences. Some of the interfering devices of the bigger type can be dealt with very easily. I cannot think that any reasonable person would object to fixing even a fairly large condenser on a lift motor, because it can be stowed away quite easily, the cost cannot be great, and the interference of a lift motor may be serious. We were a little handicapped in the aural demonstration given by the author, because we could hear the noise of the machines themselves as well as the interference which they caused. That is where the value of the cathode-ray oscillograph lies—it shows what is really happening. I do not think that steps for curing interference should be carried too far. Operating a switch in the house gives a click, and no one would suggest that all switches should be paralleled with condensers to avoid it. Further, it is not usual to have the vacuum cleaner running when one is enjoying the wireless; it would not be done because of the noise of the apparatus itself. The same argument applies to some of the other apparatus, such as the sewing machine. It is difficult to see how one can fix a condenser of any reasonable size as a self-contained apparatus on these smaller appliances of which complaint is made. I gather that the ordinary induction motor of commerce is not a great offender. I should like to ask what would be the effect of the commercial condenser which is very often used in parallel with a large induction motor in order to raise the power factor. This is quite a common arrangement, and I would inquire whether the condenser is placed in such a way as to be effective.

Mr. J. S. Forrest: I notice that the value of $+40$ decibels is suggested for the signal/noise ratio. I should like to know whether this is to be regarded as an ideal to be aimed at, or as a value which could be obtained under all practical conditions. Consideration of this value in conjunction with the minimum signal strengths in Table 1 shows that for wavelengths below 20 metres any disturbing signal which has a field strength greater than $0 \cdot 1\,\mu$V per metre will give rise to "interference." For the wave band 20 to 200 metres, a disturbance having a signal strength greater than $0 \cdot 2\,\mu$V per metre will give rise to "interference." Similarly, for the broadcast band of 200 to 2 000 metres, "interference" will be produced by any signal having a field strength greater than $10\,\mu$V per metre. I suggest that these values for interfering field strengths are much too low, and that the proposed French value, $166\,\mu$V per metre, is more reasonable and more likely to be attained in practice. Table 2, which gives the interference level from a 132-kV power line, confirms this opinion. On the basis of the signal/noise ratio of $+40$ decibels, and the minimum signal strengths given in Table 1, it would appear that this line is giving rise to severe interference on all wavelengths and under all conditions. This conclusion is not supported by practical experience on the Continent, in America, or in this country, and it is generally recognized that a transmission line insulated with the suspension type of insulators does not give rise to severe interference. In fact it may be mentioned that it is possible to obtain good reception of Continental broadcasting in daylight conditions by means of a wireless set located inside a 132-kV substation. It is stated underneath Table 2 that the noise level is rather difficult to measure, and I suggest that the values in Table 2 perhaps include noise due to sources other than the 132-kV transmission line. In Appendix 3 it is remarked that the insulators should be of such a type as to limit corona and spark discharge to a minimum. I think it should be mentioned that radio interference is not the primary consideration in the design of a high-tension transmission system, and that it is undesirable to increase the corona limit too much; in fact, it is not uncommon practice artificially to decrease it, in order that steep-fronted travelling waves may be attenuated rapidly. The wireless relay systems which are becoming so popular are a very interesting way of evading the trouble due to radiated interference, because they permit a large number of subscribers to be fed from a receiving station remote from any interference. With regard to the incidence of the cost of suppressing interference, I suggest that the necessary funds might be obtained, at any rate in part, from the licence revenue. Finally, I should like to ask the author what percentage of complaints has been traced to faults in the complainants' own wireless sets. I believe that in other countries it has been found that this percentage is quite high.

Prof. C. L. Fortescue: The gist of the subject lies in the author's last remark: it is no longer an electrical or a technical problem, but entirely a psycho-economical problem; it is a question of how much the owner of the broadcast receiver is prepared to pay for the privilege of picking up weaker signals. The cause of the trouble is the property of the arc which always forms at a break of circuit; collapsing suddenly, it sets up a surge which radiates over a wide spectrum, and every receiver which is exposed to this radiation is bound to absorb a certain amount of it. Unless we can suppress the source, the

surge, we shall have to tolerate the interference. Since there exists an organization, under the control of the G.P.O. and the B.B.C., for looking into the question of these complaints, some powers should be given to it to investigate all the complaints that are sent in. Those who send in complaints should be called on to pay a deposit, which could be returned if the complaint appeared to be justified. This would assist in finding out how much the owner of the receiver is prepared to pay for the privilege of receiving distant programmes. If on investigation it is found that owing to the interference signals of a reasonable field strength cannot be received, then this organization should be given powers to compel the owner of the interfering machine to put it into a non-interfering condition. I do not think we shall be able to eliminate the interference caused by electro-medical apparatus, except at great cost.

Mr. H. Bishop: I should like, in the first place, to raise a question concerning the title given to this discussion. It refers to the reception of radio broadcasting, but I imagine the G.P.O. and the Services are also interested in this question of interference, especially so far as the reception of short waves is concerned. There are 6 million receiving licences at the moment, and the number is still rising. This means that about 50 per cent of the homes in this country are equipped with wireless sets. The interference trouble became evident about 8 years ago, and the B.B.C., in conjunction with the Post Office, took steps to investigate it. The work was difficult, because there were, and still are, no statutory powers, and persuasion alone could be employed; furthermore, at that time the transmitters of the B.B.C. were of low power, and in many parts of the country the field strength from the nearest broadcasting station was undoubtedly low. In the last few years, however, bigger stations have been built and the average level of field strength is now considerably higher. On the other hand, receivers have become more sensitive, but the sensitivity to which a receiver is normally adjusted is very much below its maximum, at least for ordinary home listening. There have been numbers of frivolous complaints, and Prof. Fortescue has suggested that the complainant should pay a small deposit when he makes the complaint. This system is actually in operation in Denmark at the present time. The B.B.C. prepared a questionnaire, which I am glad to see the Post Office have adopted. This procedure has reduced the number of frivolous complaints considerably. The author stresses the importance of the various wave-bands and the minimum field strengths to be protected. These values are of extreme importance and merit further study. Another factor which is of considerable importance is the average depth of modulation of B.B.C. transmitters. It is generally agreed that it is impracticable to cure interference by arrangements at the receiving end, and it is therefore essential that the trouble should be cured at its source. The problem of additional cost naturally arises. The fraction of the total cost is difficult to determine, because, for example, the cost of the condenser to be connected across the contacts of a switch may be a large fraction of the cost of the switch itself. but quite a small fraction of that ratus of which the switch forms part. To protect against unfair competition, it is essential that if a suppression device be included all manufacturers should fit it. That naturally implies some sort of persuasive or legislative powers. Large numbers of listeners do not realize that they are suffering from interference, and we have evidence that the trouble is antagonizing listeners against the greater use of electricity and the development of the domestic load. In amplification of what Mr. Donaldson has said, I notice the statement in the current issue of one of the technical journals that if half the sets in the country were mains-operated, and averaged 40 watts each for 500 hours a year, the total consumption would be about 60 million kWh, equivalent to the amount sold for all purposes in a town the size of Stockport. In countries abroad there is a good deal of legislation on this subject. In Denmark, Rumania, Belgium, and Spain, there are specific laws against interference, and in other countries —notably Italy, Hungary, Sweden, Holland, and Yugoslavia—legal action against interference has been taken. Great Britain is one of the few countries in which this problem has not so far been tackled. The balance of legal principle and precedent, however, would seem to afford relief to a man whose reception is interfered with by the escape of parasitic electrical energy from electrical apparatus in the hands of his neighbour. The B.B.C., and to some extent the set makers, are blamed for interference, and it is rather difficult to convince the non-technical listener that they are not in fact to blame. The greater publicity which has recently been given to this matter, due to the Institution's Committee on Electrical Interference with Broadcasting, has led to many more complaints, which proves the contention that there are many people suffering from this trouble who do not know what steps to take to cure it. The Post Office are doing admirable work in tackling the problem, but they are overwhelmed. It is obvious that the trouble must be cured at its source, and I think that much can be done by friendly co-operation between all the parties concerned.

Mr. R. T. B. Wynn: There has been a little criticism of the suggestion that interference might be suppressed down to a level of 40 decibels (a voltage ratio of 100 : 1). Suppressors have gradually improved in their efficiency since the early days, and a far greater degree of suppression is obtainable to-day than was available in the past. Whenever a serious attempt is made to tackle this type of work the problem of what is meant by suppression arises, and there is difficulty in defining the the efficiency of a suppressor. If, for instance, signal strength and the wave bands to be protected are disregarded, it is considered that 30 decibels suppression behind most types of programmes is not sufficiently satisfactory, particularly when the interference is continuous. Consequently 40 decibels is suggested. It is of interest to note, however, that the 40-decibel condition demonstrated on the gramophone record gives a background of interference more or less equivalent in level to needle-scratch; and many people are prepared to criticize gramophone transmission on this account. Again, suppression to the extent of 40 decibels behind a symphony concert is not considered by musicians to be good enough in soft passages. The B.B.C. rents from

the Post Office music lines on which the noise level is more than 50 decibels below the level of the programme, and it is submitted that this is the sort of standard which should be aimed at in this work. Having obtained an idea of the signal/noise ratio which is satisfactory—and it is very much a matter of opinion—the next question which must be considered is the signal level to be protected. The minimum signal chosen, namely 1 mV per metre, for wavelengths over 200 metres, is one at which a modern receiver will, in the absence of interference and with automatic volume control, give an enjoyable programme. The matter has to be considered in terms of wavelengths because the levels of signal strength available are by no means as high as 1 mV per metre in the reception of short-wave services, or in the case of the ultra-short waves contemplated for television. These figures are open to criticism, but the intention has been to attempt a high standard, perhaps beyond that which can be obtained at the moment, particularly in the case of short and ultra-short waves, and to depart from this standard only when it is necessary to do so. Any measurable standard which is adopted will apply in both directions, because it will permit the manufacturer of a piece of electrical equipment to have some test applied to it which will enable him to prove, if anyone complains about his apparatus, that he at least is not guilty. Further, if the standard is too low it will regularize interference which, though it may be an improvement on the present state of affairs, will not be good enough for the future.

Col. A. S. Angwin: The art of wireless is restricted by as many regulations as any other art which is being exploited at the present time. Both international and national regulations are in force for the use of the appropriate frequencies and for the regulation of interference between wireless services. It is perhaps somewhat of an anomaly, therefore, that in this country there is no regulation whatever of a national character for safeguarding interference to wireless reception arising from other services. One of the critical questions to be decided is, can the desired regulation be obtained by means other than some form of legislation, to which apparently most of the other countries of Europe have been driven? While we are attempting to regulate interference it is important to bear in mind the development which is taking place on the shorter wavelengths; they are being used more and more for commercial purposes, and it must not be forgotten that the development of television is only possible on the short wavelengths. Comment has been made on the more stringent conditions to be applied, as regards the field strengths which can be tolerated, in the case of these shorter wavelengths. Whilst this condition is essential, it is, however, fortunate that the interference on these frequencies is not usually of such a high order as on the lower frequencies, and the propagation is more rapidly attenuated. It is equally important to consider this range of frequencies, and I am quite sure that, had it been possible to demonstrate here a television experiment, the mutilation on television caused by unprotected apparatus would have shown up even more than the audible interference effect on the broadcasting wavelength.

Mr. A. J. Haswell: Commercial motors, which include those for lift machinery, although possibly efficient for their duty, are the chief disturbing factors in radio interference, commutation being the chief difficulty, especially on d.c. circuits. We have frequently found such a motor to contain brushes of various grades, and there is in the brush situation great opportunity of helping the suppression of interference. We are rather too much inclined at present to fix condensers or other suppressor apparatus across a troublesome motor, without first ascertaining whether the noise can be cured by adjustments or a slight alteration in design which can easily be arranged with the manufacturers. A large number of experiments have been made with various grades of brushes, and the variations observed are wide. I should like to mention one interesting point which may in future engage our attention in connection with radio interference, namely, that in accepting the fact of audio-frequency sympathy between a motor (or dynamo) and a radio receiver there has recently arisen the interesting possibility of the frequency of the mechanical noise of the machine being that of a harmonic of the supply frequency. Instances of this have been observed, and within the last few days experiments have been carried out on a pump motor where, in addition to the motor noise, the pump pulse and working noise were also faithfully reproduced.

Mr. L. B. Turner: We have had some excellent demonstrations of that class of interference in which it is technically possible for the injured person to protect himself; but we must not forget the other class, where the antenna is located in the disturbing field. If this field is not suppressed at the source, for technical reasons no escape is possible short of removing the antenna to another part of the country. In the problem of electrical interference with broadcasting, a mere accidental by-product of one kind of appliance is destructive of the essential action of another kind of appliance: surely a condition not tolerable in a civilized society. Some form of compulsory control is necessary, and this makes the ability to measure the amount of the interference very important. The author and many other speakers have referred to the noise level; the noise is said to be so many decibels above or below a signal of 1 μV per metre. Now the decibel notation serves to compare powers without reference to their qualities, but it is as otiose to say that the noise is so many decibels above the signal, without specifying the nature of the noise and of the signal, as it is to say that a certain yellow light is so much brighter than a certain red light; their relative values depend on the way the light is being used, on the nature of the eye that sees it or of the plate or photo-cell that is being influenced by it. This contention was illustrated by the gramophone record which the author played. We had a speaker with a "boomy" voice, and the interference which was superimposed was of a high-pitched character; I see no significance in the statement that the one was 20 decibels above or below the other. Are the r.m.s. values being compared? Or is it the squares of the peak values, or some other function, of the two trains of sound? It is very important for any advance in dealing with interference that we should both be able to measure and

know what we want to measure. We want available better police work, as it were, in this matter, than we have in the suppression of noisy motor-cycles. The noise of the motor-cycle is illegal, but because it cannot be, or is not, suitably measured the regulations are not enforced. Turning now to the origin of the interference: we know that it emanates from a circuit undergoing a sudden change of current, a discontinuity. Commonly this is caused by some form of make or break of circuit (generally between metal contacts), and sometimes owing to the curious behaviour of a gaseous conductor. I think in practice the break matters more than the make, and I have made a brief calculation to illustrate this. As an example of a system which can be set into oscillation and so interfere with wireless receivers, I take a piece of 100 lb. air-line loop $\frac{1}{10}$ mile long. This will have an inductance of some $400\mu H$ and a capacitance of some $800\ \mu\mu F$, and may be represented approximately by the circuit of Fig. A. If a current of 10 amperes flowing between A and B is suddenly interrupted, an oscillation arises of frequency about half a million cycles per sec. and with initial peak rate of change of current of about 36 million amperes per sec. It is this value

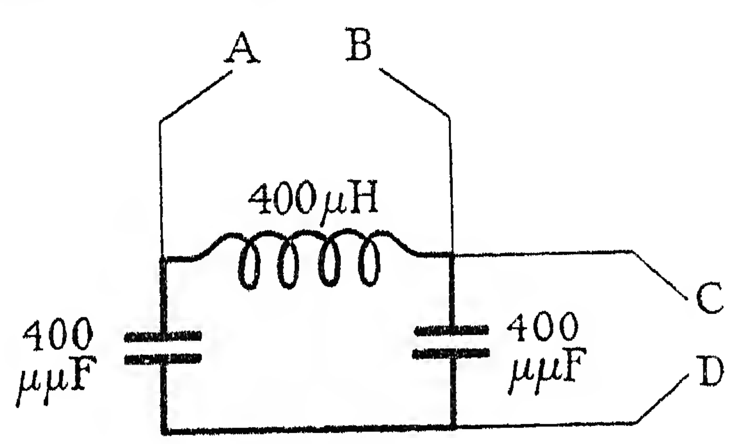

FIG. A.

which determines the strength of the disturbance radiated from the system. Now consider what potential difference suddenly applied across CD would produce an equal rate of change of current. It is readily calculated as about 14 kV. This suggests that breaks rather than makes are likely to be the more troublesome. As to the spark which may occur at a break, this serves to make the break less sudden. I think the spark should be regarded as an alleviating symptom rather than as a cause of the trouble. Whether a break drawn out by a spark ever causes more disturbance than an ideally sudden break is an interesting subject for investigation.

Mr. C. C. Paterson: Mr. Wynn pointed out that Great Britain was the only large country which up to the present had not introduced some regulations; this may be rather a matter for pride than shame, because one can rush into regulations too soon. There are many now who speak of enacting legislation, but it is quite clear from this discussion that, even if we had the opportunity, none of us would know exactly what to lay down in the way of regulations to secure a practical cure for the trouble. It is very easy to say that every interfering person will be held responsible for the interference he causes, but that would not be satisfactory; there must be a practical way to surmount the difficulty. The wireless enthusiast is sometimes said to be trying to clear everyone else off the road just because he wants to make his apparatus work satisfactorily. I think that many who allege this forget that the rest are not using the road for any legitimate purpose; in effect, but in all innocence, they are throwing obstructions in the way of the legitimate users of the road. The wireless enthusiast is often called a late-comer, and it is said that therefore he must get on as best he can; but he is not a late-comer in the highway that others are using; he has a highway of his own, and it is the only one he can use, so that he ought to be considered in the matter. More important than this, however, are the big industrial and public issues which will depend more and more upon a "clean" ether for radio purposes. A very great deal will depend on the attitude of the manufacturers, on whom it will rest to try in a practical way to apply these devices to their apparatus, and to do so cheaply. Is it impossible that all new apparatus sold and installed in this country should have suppression devices incorporated? This, coupled with the steady obsolescence of existing apparatus, might then gradually bring about a cure of the worst of the trouble.

Mr. W. F. Floyd: The remarks of a number of speakers in the discussion have implied that interference is caused mainly through an irregularity in the operation of a machine. It must be understood, however, that interference may be caused by the normal operation of machinery, as is indicated by what Mr. L. B. Turner has said. If a manufacturer proposes to put a machine on to the market which is to be unimpeachable from the radio-interference standpoint, he must incorporate in it a disturbance-suppressor unit, no matter how well designed his machine may be. This, however, by no means disposes of the problem. Under certain conditions, a particular disturbance-suppressor unit may resonate with the circuit to which the machine is connected, the resulting interference being more serious, possibly, than if no unit at all were employed. Further, the particular type of suppressor-circuit arrangement which is found suitable for one machine in a certain situation is unlikely to be effective universally. Even should a particular suppressor-circuit arrangement be found effective universally, an economic consideration arises, for the particular suppressor device in this case would clearly be that which produced the maximum attenuation of the interference generated by the machine, and hence it would be likely to be the most expensive as far as initial cost is concerned. It is economically unsound that every user of a machine should have to pay for equipment which is only required in, say, 2 installations out of every 10. The whole problem should be approached, therefore, *in situ*, and not in the factory where the machine is made. With regard to the matter of the relative levels of the desired signal and the interference, it seems to me that before any quantitative data can be put forward as a basis for legislation, some research work will have to be carried out on the extent of the "masking" of one sound by another of different intensity, pitch, and wave-form factor. I do not understand at present what is meant by the difference in level of the two signals in this context. Both the subjective aspect of the problem and the purely objective matter of the definition of terms have to be investigated and explained.

Mr. H. C. Turner: I notice that the author does not refer to the capacitor motor, which is on the market in America and contains a suppression device in its

own frame. The manufacturers claim that this motor satisfactorily prevents interference with wireless reception in the neighbourhood, and I think it is well worth while for these claims to be investigated. I should like to ask whether the Post Office have any statistics of the incidence of interference. After all the investigations made, the Post Office could surely give a map showing the "black" spots for each area. I think we can disregard those cases where the culprit is also the victim; so that vacuum cleaners and hair dryers, except when two or three are gathered together, as in a barber's shop, can be ignored. So far as the motors of lifts, neon lights, and electro-medical devices are concerned, the householder is very much in the hands of the owner of the block of flats, or of his neighbours.

Mr. C. E. G. Bailey: The question of the modulation percentage used in definitions of signal strength has been mentioned but not actually discussed. Presumably the figures quoted by the author for the signal/noise ratio in connection with the gramophone record were given for field intensities when the sounds were equalized. On the other hand, in comparing the ratio of a broadcast signal and an interfering signal the field intensities of the waves radiated are compared. The interfering signal has no carrier wave and, roughly speaking, corresponds to a carrier wave modulated 100 per cent. If, therefore, one compares this sound with that which is produced in a broadcast receiver by a carrier wave modulated approximately 30 per cent, one must add 6 decibels to the ratio between the signal and the noise in order to obtain the same comparative results. For example, if a broadcast transmitter is modulated 30 per cent and one wishes to obtain a signal/noise ratio of 20 decibels, then the noise must be attenuated to 26 (and not to 20) decibels below 1 μV per metre. This argument applies to an even greater extent in concert transmissions, in which, in order to maintain an effective crescendo, the average modulation percentage may be lower than 30 per cent.

Dr. L. E. C. Hughes: The noise in radio sets due to an external noise-field adopts the carrier of the required transmission, and therefore the comparison should be made between the integration of the noise-field as compared with the integration of the side-frequencies of the required transmission over a specified frequency band. If this comparison is to be made with a field-strength measuring set, it is necessary to tune out the carrier with an acceptor shunt of very low decrement. I have had considerable experience of measuring speech/noise ratios by a method originally proposed by A. H. Reeves* for high-grade microphones, but which is easily adaptable to other high-quality circuits such as are used in broadcasting. In principle, the speech output of the transmission is attenuated, by a standard attenuator, until the speech just vanishes into the noise. In practice it is not possible to attenuate speech apart from noise in a single channel, and therefore the speech from a source of similar quality is attenuated and mixed with the output. Two microphones are placed side by side in a damped room, with their outputs correctly mixed and with their series attenuation adjusted so that, on repeated switching, their speech outputs appear to be of equal level. The microphone under test is then placed in a sound-proof box or in another room, and the speech output of the comparison microphone is adjusted by series attenuation until a consistent comparison is obtained with the noise output from the test microphone. The increase in attentuation of the comparison microphone is then taken as the speech/noise ratio. With practice, agreement within about 2 decibels is possible, because the point at which some words, and not the sense, in a conversation can be detected through typical noises is fairly critical. The chief difficulty is in deciding upon the listening device, since an indicating device is not permissible on acoustic grounds. I have heard elsewhere the record which has been demonstrated here by the author, and have received totally different impressions of the speech/noise ratios recorded on it, owing to the difference in the reproducing response curves. For the highest-quality performance, such as it is hoped to obtain in broadcast reception, it would appear necessary to use moving-coil head-receivers on which to detect the balance of speech and noise. These were used in the method described above. For the routine measurements of speech/noise ratios in domestic receiving sets on location, it is necessary to use a portable outfit which generates normal announcers' speech of high quality and attenuates this in known steps until an aural balance is obtained with the noise normally developed by the receiving set, when adjusted to normal gain. This also applies to external noise-fields, the test being performed with an unmodulated carrier.

* *Electrical Communication*, 1929, vol. 7, p. 258.

Mr. J. M. Kennedy: From the paper, and more especially from the experiments shown, it would seem to be impossible to have an all-electric house and yet to receive broadcasting. I have in my house examples of nearly all the apparatus shown by the author, and I experience perfectly good reception. What is the reason? How did the author obtain the results he has demonstrated, which to my mind exaggerate altogether the difficulties? I think it is incorrect to say that scientific development has reached such a stage that it is impossible to improve radio apparatus. Surely radio receivers can and will be improved to such an extent that these small domestic appliances will not cause any interference. I am surprised that the author did not include in his experiments the interference obtained from an ordinary Post Office telephone receiver. I can show him examples where such interference is the most serious disturbance in an all-electric house. It would be interesting to know whether the Post Office are installing condensers on all their telephones and extension switches.

Mr. H. B. Swift: With reference to the questionnaire issued by the Post Office, I consider that the most important question is omitted. It is: "Give the date when the set was purchased." There are many sets in use to-day which have been in existence for 6 or 7 years, and in which selectivity is almost absent, and it is in connection with these sets that complaints generally arise. The answers to the question I have mentioned would no doubt settle many disputes and probably lead their owners to obtain more up-to-date receivers, which would not be so prone to pick up interference. With

regard to the interference caused by trolley-buses, I think that much of the trouble here is due to the fact that the vehicle is entirely insulated by the rubber tyres. In view of the fact that metal bodies are rapidly becoming the standard, and that if a leak occurs on a trolley-bus fitted with a metal body serious trouble may arise, something ought to be done in the way of earthing the vehicle. I suggest that it would be possible to fit a steel thread to the tyres, which could be connected to the body of the vehicle. This would not only have the effect of preventing boarding passengers from getting shocks, but would also, in conjunction with the insertion of suitably-connected condensers, considerably help in preventing radio interference.

Mr. E. W. Braendle (*communicated*): The author does not refer to the interference caused by small generators employed as accessories to the receiving apparatus. The methods necessary for the elimination of interference derived from a small motor-generator set used as a source of power supply for a wireless set are far from having the degree of simplicity indicated by the author, particularly when a high-gain receiver is operated on short wavelengths. This type of plant radiates at one or more (usually more) definite frequencies, the value and multiplicity of which appear to have little reference to the type of generating plant employed. For some time past it has been common practice to fit special chokes, condensers, or a combination of both, to the generator, to overcome its own individual form of radiated interference. In certain cases complicated filters are necessary, upon the design of which considerable time and expense has been expended. I should like to ask whether the author can give any information on the following points: (1) The relative intensities of radiated interference over the spectrum of frequencies above 3 000 kilocycles per sec. (including harmonics of lower frequencies), with particular reference to the ultra-high frequencies, for any given type of apparatus. (2) The extent to which both frequency and intensity are affected by the design of the apparatus. (3) The manner in which the initial design could be modified so as to reduce the need for the subsequent application of filters. (4) The extent to which the intensity/frequency curve varies for motors and other apparatus of identical type.

Mr. L. Friedman (*communicated*): I shall confine my remarks to two kinds of interference. The first is that from automobiles and aircraft, i.e. from the coil- and magneto-ignition systems of petrol engines. It happens that the only prospects for a television service appear to be on the ultra-short-wave band, and therefore the abolition of interference on this wave band is of the greatest importance to the further development of television. The difficulties encountered in radiating on ultra-short waves with a comparatively high power, and the strong attenuation of the very high frequencies involved, considerably decrease the signal/noise ratio. In addition to that given by the usual screened wiring and the fitting of special suppressors (resistances) at the sparking plugs, considerable freedom from interference can be obtained by careful design. In some cases, where the design is such as to minimize the interference, it is not even necessary to take other precautionary measures. Experiments have shown that interference on ultra-short waves varies considerably with different makes of cars. With the new Ford car very little interference seems to be produced. This is no doubt due to the unusual position of the distributor, making the connecting links from the distributor to the sparking plugs very short. In any case, practically no interference has been observed on an ultra-short wave set operating at a few yards from the running engine of this type of car. On the other hand, some very bad interference has been experienced with other well-known makes. Interference on ultra-short waves from motor-cars can be minimized inexpensively, and to such an extent as to make it negligible. There are two factors which will, in time, decrease this type of interference; one is the increasing use of car radio sets, and the other the use of crude oil for motor-cars. Nevertheless, legislation to stop interference will be necessary sooner or later, as ultra-short waves may be very useful in other special circumstances, besides their use in television. With regard to my second point, I should like to know why condenser suppressors are not fitted by the G.P.O. on automatic telephones. The dialling produces interference noises, which, in certain instances, are reported to be very serious. Interference of this sort is noticeable on all but the local B.B.C. transmitters.

Mr. F. T. Lett (*communicated*): The author expounds the ideal condition in which the interference is suppressed at the source. This condition is not likely to be met with in practice for some time, but unless something is done immediately the sale of large receivers will be ruined, as approximately 85 per cent of these are sold to customers in town areas. Much can, however, be done by the radio manufacturers themselves in designing better receivers. The receiver and the lead-in system should be so screened that only electric waves induced in the horizontal part of the aerial are received. This means screened aerial leads, an efficient mains filter, and careful screening of all coils and wiring in the receiver itself. In very few instances has it been found that a static level of more than 15 μV per metre (wavelength 200–2 000 metres) exists at a height of 20 ft. above a building. A well-screened set, when used in areas of high noise level, will not reproduce any noise from the loud-speaker if the aerial is removed. When a receiver with a sensitivity of 1 μV is used in an area where a static level of, say, 100 μV per metre exists, the effective band width of the receiver largely determines the signal/noise ratio. A sharp low-frequency cut-off which is variable, either automatically or manually, gives effective reduction of noise, usually without loss of intelligibility (as in normal telephone practice).

Mr. H. S. Pocock (*communicated*): The author refers to the Committee appointed by the Institution to study the question of interference and to report to the Council. Naturally, the proceedings of this Committee are confidential at this stage, but a report* on the progress made was recently issued with the authority of the Institution. It was stated in this report that the Committtee "reviewed various possibilities of bringing suppression devices into use without having recourse to legislation." Does this mean that there is any general

* *Journal I.E.E.*, 1933, vol. 73, p. 543.

feeling that legislation should be avoided? If some general agreement can be reached in the electrical industry on the subject of suppressing interference, then it would seem to me that that moment should be seized upon to introduce legislation to ensure that agreement continues. There can surely be no objection to the legal enforcement of a policy on which those affected are already voluntarily agreed. In the absence of legislation there will always remain the probability that whilst some manufacturers will co-operate and fit suppressors to their apparatus, others in competition with them may decline to do so. Such a state of affairs will obviously be unfair. Legislation could take into account that a period of time should be allowed before the law became operative and that, in the case of existing installations, evidence of interference would have to be produced before action could be taken. There must be very many instances where plant does radiate but without causing interference with wireless reception. The question of who shall bear the cost of making apparatus interference-free is, I believe, the chief obstacle at present. Cannot this be met on the broad basis of the benefit to the industry as a whole which must result from increasing the popularity of electricity in the home? Again, if legislation were introduced it would seem that it could be turned to good account by the British manufacturer, since foreign apparatus could no longer be imported until it was made interference-free. The benefit of this hold-up, if only temporary, should go some way towards offsetting the cost, in certain branches of the industry, of fitting suppressor devices to new equipment of British manufacture.

Mr. M. G. Scroggie (*communicated*): It seems to me that the point raised by Mr. L. B. Turner is of great importance. Sounds of different frequencies cannot be compared unless account is taken of the variation of sensitivity of the ear with frequency. Thus the difference in threshold intensity between a note of 100 cycles per sec. and one of 2 000 cycles per sec. is about 40 decibels, which is not a negligible factor in the matter. If in the sound-measuring apparatus a network is included to attenuate the frequencies to which the ear is less responsive, it holds good only at one level of intensity: for louder sounds the difference is much less than 40 decibels. It would appear, therefore, that very careful consideration is necessary in defining the tolerable signal/noise ratio, for it depends on the frequencies of both sounds. In fact, the figures given in the paper are quite meaningless.

Mr. A. Morris (*in reply*): The discussion has mainly centred around the two chief aspects of the question, namely the technical and what may be described as the political. In regard to the latter aspect, the question is that of the regulation of electrical interference either by legislative measures or by voluntary means other than legislation. Mr. Donaldson and Mr. Paterson have spoken fully on this matter in very sympathetic, and what will doubtless be regarded by all interests as extremely conciliatory, terms. Prof. Fortescue and Col. Angwin have also contributed by clearly posing the essentials of the question. Mr. Pocock raises issues with the Committee appointed by the Institution, which issues will doubtless be fully considered. The final answer to this question is not within my province. It is a vital question and will doubtless be settled by the interested parties when it has been fully explored. I shall content myself by pointing out the advantages of voluntary regulation in the first instance, backed by legislation at a later date and at a time when the electrical industry requires legal means for regularizing and protecting its interests.

If the whole question of electrical interference is not to be shelved, definite technical requirements must be laid down, no matter what the nature of the political settlement may be. It is these technical considerations with which I am concerned and it was the main object of the paper to suggest a simple practical, technical basis upon which the question may be dealt with.

For the sake of simplicity of statement and of ease and smoothness of operation, in the case of any regulation which may ultimately be framed, it is desirable that the large number of variants with which this question is concerned should not be permitted to complicate the issue unnecessarily. If this can be safely accomplished, and in my view it can, then there is actually only one fundamental quantity which it is necessary to define, measure, and limit in magnitude, namely the maximum permissible value at the receiving site of the radio noise field due to an item of electrical plant. Clearly it is this quantity which the manufacturer of electrical plant urgently requires to be advised of, if he is to make any progress towards a settlement of the question. An expression for the computation of this quantity, in terms of certain other quantities, is furnished later in this reply. These latter, the magnitudes of which have already been quoted and which appear in the paper, constitute the basis for arriving at this fundamental quantity and consist essentially of a satisfactory value for the signal/noise ratio at the output of the receiver, the minimum value of broadcast field strength to be protected (to the ultimate degree envisaged by the aural signal/noise ratio), and suitable average limits to the figure representing the degree of modulation of the broadcast transmission.

Various criticisms of the figures quoted in the paper have been made, notably by Dr. Hughes and Messrs. Forrest, L. B. Turner, Floyd, and Scroggie. In the main, the criticisms have not been of a constructive character and as a consequence it may be correctly inferred that a completely satisfactory and rigidly scientific solution of this question is not at present available.

The criticisms can perhaps best be dealt with by amplifying the statements made in the paper. It will be well to say at the outset that the proposals are based upon the principles employed in the present-day engineering technique of radio communication circuits, and that the application of this practice to the question in hand will permit of considerable progress being made towards a technical settlement of the question.

It may be assumed that the interference set up by an item of electrical plant consists of an infinite series of uniform steady-state voltages at radio frequency, distributed in a continuous spectrum. When these components are combined with the signal carrier and are passed through the detector of a radio receiver, an

infinite series of beat-notes will result. Of these beat notes, those which are within the audible range and within the acceptance band of the audio-frequency amplifier of the receiver will appear as noise at its output terminals. The mean-square value of the interfering radio-frequency voltages can be measured in terms of an equivalent radio noise field-strength, by means of a receiver suitable for the measurement of carrier fields; for example, the receiver described by Messrs. Friis and Bruce in the *Proceedings of the Institute of Radio Engineers*, 1926, vol. 14, p. 507, in a paper entitled "A Radio Field-strength Measuring System for Frequencies up to 40 Megacycles." A description of the set used for the measurements recorded in Table 2 has been added to the paper as Appendix 5.

Under practical interference conditions the receiving aerial is influenced in general by the carrier field, S decibels relative to 1 μV per metre, modulated by a signal to a degree of m decibels, as well as by an equivalent radio noise field, N decibels relative to 1 μV per metre. The resulting audio-frequency output is a mixture of signal at one particular average level and of noise at another average level. It is the ratio of these two levels which is referred to in the paper as the audio signal/noise ratio, X decibels of the transmission. In the gramophonic demonstration, the various quoted values of signal/noise ratio also referred to this quantity.

The magnitude of the signal/noise ratio in any particular broadcast transmission may be obtained from volume-indicator measurements of the level of the signal in the absence of the noise field, and of the level of the noise in the presence of the unmodulated signal carrier.

In any particular case the level of the noise in the presence of the unmodulated signal carrier will be n decibels greater than the level of the noise in the absence of such carrier. Calculation from a noise-level measurement made under the latter condition would result in a value n decibels greater than the true signal/noise ratio of the transmission.

The actual interfering effect of the noise will depend upon the value of the signal/noise ratio; the greater the interfering effect, the smaller the ratio. It will also depend, however, upon the character of the noise, i.e. whether the noise consists of complex sounds or of single-frequency tones. The continuous, periodic, or intermittent nature of the noise, as well as the actual power-level at which reception takes place, e.g. whether at headphone or at loud-speaker strength, will also govern the result. These latter features have been properly raised in criticism of the suggestion to utilize signal/noise ratio only as the criterion of reception. The criticisms are not, however, as serious as they would appear, since the figure of 40 decibels, recommended in the paper as the desirable objective for the value of signal/noise ratio in the reproduction of high-quality broadcast matter, does in fact take into account all these features. It applies only to continuous or steady interference of the type which gives rise to complex sounds of a character common to the interference from electrical plant, and relates to a power-level which is adequate for satisfactory loud-speaker reception. The gramophonic demonstration presented in this connection was governed by these features. It gave a reasonably accurate aural indication of the effects of noise, present in various degrees, upon a programme, although it is conceded that the unavoidable presence of needle scratch slightly marred the demonstration of the 40-decibel signal/noise condition. The demonstration undoubtedly emphasized the widely divergent opinions on the question of what constitutes a tolerable amount of noise, although there appears to be general agreement that a signal/noise ratio of 40 decibels represents essentially interference-free conditions.

The permissible strength of the radio noise field at the receiver can be deduced from the strength of the signal carrier field and the signal/noise ratio, etc., by the following expression, the various symbols in which have been previously defined:—

$$N = (S - m) - X$$

No misconception appears to have been caused in regard either to the measurement or the actual magnitude of the minimum value of broadcast field strength to be protected. Objection to certain of the figures has, however, been raised on the ground that so far as the short-wave and ultra-short-wave bands are concerned, too weak a field would thereby be protected. The figures of 20 μV per metre and 10 μV per metre respectively, are based upon the average fields with which the services in such bands are commonly called upon to operate. The objection to them is hardly valid, since it appears to arise from apprehension as to the practicability of protecting them to the recommended degree. In regard to the figure of 1 mV per metre for medium-wave and long-wave transmissions, it should be pointed out that individual receivers will in general be thereby protected only in respect of their respective national broadcast service transmissions.

As a matter of interest I include a Table (see page 261) giving representative signal and noise field values, appropriate to the operation of long-distance radio communication services, for which much smaller values of signal/noise ratio than are required for broadcasting can be tolerated.

A signal/noise ratio of 5 decibels will permit of satisfactory aural reception on commercial telegraphic services, which can often be operated with signal fields as low as 1 μV per metre.

I propose now to reply in detail to the remarks of various speakers. I agree with Mr. Donaldson that steps for the suppression of interference should not be carried too far. There is, of course, no need to deal with occasional interference of the type produced by the operation of some types of switch. It is true that the ordinary type of induction motor gives little trouble. The question of the use with such machines of parallel condensers for starting and power-factor-correction purposes has also been raised by Mr. H. C. Turner under the title of the "capacitor" motor. Machines so equipped produce little interference, but the freedom is inherent in the type and the condenser functions from the anti-interference point of view only during switching operations at starting.

In reply to Mr. Forrest, the value of 40 decibels for signal/noise ratio is a recommended standard to be aimed at. Taken in conjunction with the recommended values

of minimum field strength to be protected, it is thought that it should be capable of practical realization in all but exceptional instances. The values for permissible noise field deduced by Mr. Forrest from the paper will require to be reduced by a number m, representing the degree of modulation of the signal carrier in the manner already explained. This circumstance, of course, lends additional support to his contention that serious interference will be experienced immediately beneath the high-tension transmission line dealt with in Table 2. Whilst agreeing with this contention, it should be pointed out that at $\frac{1}{4}$ mile from the line the 2 000-metre noise field has diminished by some 30 decibels and the 20-metre noise field by some 20 decibels, and that in consequence the standards recommended in the paper as representative of essentially interference-free conditions would in fact be approximately realized at such a distance from the line in question. There is no reason to suppose that the values given in Table 2 include noise due to another source; attenuation/distance measurements, made at the time of these tests, quite discount the suggestion. In regard to the figure of 166 μV per metre which Mr. Forrest refers to as "the proposed French figure," if he suggests that it should be considered as a basis for interference suppression work in this country then it is very desirable to point out that the figure has not been accepted by the French Post Office, neither has it any statutory backing whatever in France. It is agreed that radio interference is not the primary consideration in the design of a h.t. overhead system. Nevertheless attention can be given to it without deleteriously affecting the main object of the design. Current literature, in fact, indicates that the contrary effect is achieved by designs which ensure increased radio-interference corona voltages. Wireless relay systems are not free from interference troubles. If the reference to these systems is intended to convey the suggestion that the question of radio interference should be resolved by general recourse to them, then perhaps it should be stated that their popularity is such that the subscribers to these systems constitute only a small percentage of the total number of broadcasting listeners. I am rather averse to quoting figures which purport to represent either the extent of, or an analysis of, complaints of reception from listeners. Such figures can be very misleading. It can be said in regard to faults, however, that faults in radio receivers, in house and distribution wiring and cables, as well as in overhead transmission lines, are at times responsible for poor reception conditions.

Signal and Noise Field Values for Communication Services.

	Long-distance telephony services	
	Long-wave	Short-wave
	Decibels relative to 1 μV/m	
Average signal field	20	26
Minimum operating signal field.	0	2
Average noise field	—	6·5
Average range of noise field .	10 to 30	— 1 to 14

It is interesting to receive Prof. Fortescue's confirmation of the concluding sentence of the paper. In regard to his reference to the arc it may be stated that experience shows that the more sudden the collapse, the greater is the interference; long-drawn-out arcs in heavy-current circuits produce less interference than the shorter-period sparks of small-current circuits. An example of this is to be found in the trolley-bus. If the trolley arm is jerked from the overhead conductors when the bus is standing with only its lighting circuits switched on, the interference is much greater than if the similar operation is performed when the bus is running with the traction motors in action. Furthermore, in the case of essentially sparklessly commutating motors, in which the spark is minute and of short duration, the interference may, for the same reason, be very intense. Mr. L. B. Turner has also referred to this matter, and his calculation, which suggests that the breaking of a circuit is more troublesome in the matter of radio interference than the making of a circuit, is certainly borne out in practice. As indicated above, a very short-duration spark gives much more interference than a long-drawn-out arc, which latter may accordingly be regarded as an alleviating circumstance in the breaking of an electric circuit.

Referring to Mr. Bishop's remarks, it is quite true that all radio communication services are concerned in the question of radio interference, and that, in addition to the B.B.C., other authorities, such as the naval, military, air, and police, as well as the General Post Office, are interested. Mr. Bishop's brief survey of the question is interesting and I am obliged to him for his supporting data relative to Mr. Donaldson's remarks that in the aggregate the radio load is not an insignificant one. Furthermore, in assessing the value of this load to the undertakings it must not be lost sight of that customers actually purchase many times this amount for other domestic purposes and that their numbers are liable to be increased by an amelioration of the existing radio-interference conditions. A census which has recently been compiled by an undertaking supplying over 10 000 customers, disclosed the fact that 27·82 per cent of the customers' premises were equipped with all-mains-operated sets, 13·55 per cent with h.t. eliminator and l.t. accumulator-operated sets, and 7·35 per cent with battery-operated sets.

The explanation given by Mr. Wynn of the main considerations which lead to the figure of 40 decibels as the desirable objective for the signal/noise ratio is very informative. He points out that in the comparable case of Post Office trunk lines, the noise-level on such circuits is more than 50 decibels below the transmitted programme. Actually for international cable circuits a signal/noise ratio of at least 55 decibels is required, and in order to achieve this overall result on such circuits the noise on the actual lines is arranged, by special cable-balancing operations, to be very considerably below this level. Mr. Wynn also points out the necessity for the recommendations which have been

made in the paper in regard to the minimum field strength to be protected. Perhaps with the desire to be as conciliatory as possible, he suggested that in respect of the short and ultra-short wavelengths the recommended standard may be regarded as somewhat high. Without wishing to be one whit less reasonable in regard to the requirements of the matter, I should like to emphasize that the Post Office radiotelephony services are capable of working on fields of zero and of 2 decibels, relative to 1 μV per metre, for long-wave and short-wave circuits respectively, under favourable noise conditions, and that unless such fields are protected from noise to a reasonable degree, valuable traffic time will be lost to such services. Mr. Wynn emphasizes a matter which has been dealt with in the earlier portion of this reply, namely the needs of the electrical manufacturer in the matter of standards of suppression. There is no doubt whatever that this need is urgent; in fact the present-day attitude of manufacturers to requests for the suppression of interference may be summed up in the words "if you can tell me exactly what you want, I will try to give it to you."

Amongst other matters, Col. Angwin has referred to the fact that a number of European countries have been driven into legislation on this subject. Without doubt, the indications are that such legislation has been hastily conceived, since in no case have technical data, governing the degree of suppression to be achieved, been embodied in the decrees. As a consequence it is considered that the administration of such decrees will prove very unsatisfactory. Col. Angwin has also pointed out what may be regarded as a fortuitous feature of the interference from electrical plant on short waves, namely, that in general such interference is at a lower level than that on the longer waves. In regard to the ultra-short waves, the future of television as well as that of short telephony links for inland purposes and for the spanning of estuaries and narrow seas lies with their development. Difficulties are already being experienced in such development by reason of the interference from spark ignition systems.

Mr. Haswell's statement that commutation is an important factor in the interference from d.c. motors is agreed. The type of brush as well as its adjustment will certainly also influence the results. Interference may exist, however, even with seemingly sparkless commutation, and at times to a much greater degree than under serious sparking conditions. Mr. Haswell's observations on the audio-frequency sympathy between an electric motor and a radio receiver are interesting. The effect which he has noted, however, may be ascribed solely to the reaction of the mechanical load on the motor upon the flow of current in its electrical circuits. In many cases such reaction would be rhythmic and would certainly be so in the case of the pump motor which Mr. Haswell quotes.

It has been stated in the paper that if the aerial is located in an interfering field, nothing can be done at the receiver to alleviate the effects of such a field. Mr. L. B. Turner has emphasized this fundamental feature, and, since the fact is so frequently questioned, his remarks thereon are very apposite to the subject of the paper. Mr. Turner also agrees that if progress is to be made towards a settlement of the question, measurements must be made. He is, however, critical, and perhaps justly so from a strictly scientific point of view, of some of the engineering means which have been suggested in the paper and discussed during the meeting. In the earlier part of this reply certain features of the paper have been amplified. It is hoped, therefore, that the additional explanation which has been given will commend the suggestions which are put forward as a practical technical basis in dealing with this subject.

Mr. Floyd is quite correct when he says that radio interference is not confined to faulty plant but may arise from a machine which is functioning normally. The statements leading to the conclusion that radio interference should be dealt with *in situ* and not in the factory are thought not to be generally sound. In regard to the conclusion it may be said that the present-day irresponsibility in regard to the suppression of interference arises mainly because electrical plant is sold in an interfering condition.

The correctness of Mr. Bailey's argument is agreed. The expression for noise field in terms of signal field, signal/noise ratio, and degree of modulation of signal carrier, which has now been given, perhaps cover Mr. Bailey's remarks. Mr. Bailey has made a slip in expressing a 30 per cent modulation as 6 decibels; the value should be approximately 10·5 decibels.

The point raised by Dr. Hughes at the beginning of his remarks is of great importance. It relates to the determination of the true signal/noise ratio of a radio transmission subjected to noise. It has been dealt with in the earlier part of this reply, in which it is shown how a discrepancy of n decibels may arise in such determination. The magnitude of n may be as much as 15 in some cases. Calculations of the upper limit of permissible radio noise field, which involved this discrepancy, would accordingly be some 15 decibels high. Dr. Hughes's description of the methods of measurement employed for the determination of the speech/noise ratios of microphone and of broadcast receiver outputs is very interesting. He has commented upon the gramophonic demonstration from the point of view of the audio response of the instrument. Since a high-class commercial instrument was employed, it is presumed that the contention is that the average listener's reproducing conditions were not sufficiently closely simulated. This is true, but it is considered that the discrepancy does not seriously invalidate the approximate quantitative conclusions which may be arrived at from the demonstration.

In reply to Mr. Kennedy, it should be stated at once that the demonstration aimed at conveying an idea of the character of the noises introduced into a radio transmission by the operation of electrical plant. The level of the noises was purposely increased not only for this purpose but also for the purpose of demonstrating the effectiveness of the suppression devices. Mr. Kennedy's freedom from interference is possibly due to his motors being of the a.c. induction type and it is also likely that he quite properly regards as innocuous the occasional or intermittent interference from switches of the hand-operated or electrically-operated type. In any case inspection would disclose the reasons. Actually

telephone switching apparatus is referred to in the paper under Class B interfering plant. Such interference can be suppressed and, although it is of but occasional character, the Post Office deals with all justifiable cases of complaint arising under this head.

In reply to Mr. Swift, a radio receiver operating from an aerial located in an interfering field is not greatly immunized from noise by improvement of its selectivity. With regard to trolley-buses, the trouble lies with the overhead network which radiates the interference produced by the bus and power-station equipment. It is thought that the insulation from ground of the vehicles does not materially affect the position; some tramway systems give rise to severe interference.

In reply to Mr. Braendle, the small radio accessory motor finds a place in Class A (ii) plant. The interference from such items when literally embodied in the receiving equipment will of course be considerable. Exactly the same simple principles of suppression as have been described in the paper may be successfully employed. Complete screening of the machine and its supply leads should be effective. In this case it is also the preferable cure. Alternatively, multiple-unit suppressors will be needed in order to obtain suppression to the desired degree. In this connection the inductance inherently associated with the condensers, and particularly the inductance of connecting leads, will require to be controlled, especially for the purpose of ensuring suppression of the highest frequencies. In general, it will be found advantageous to use condensers of small capacitance. Radiation from connecting leads, which will require to be as short as possible, must also be controlled. The data which Mr. Braendle has requested cover a wide field and it is regretted that complete information is not available. However, in regard to (1) the interfering fields in the immediate neighbourhood of an electrical item are very complex and do not obey the laws of radiation; it is doubtful whether accurate measurements are possible. In regard to (2) and (4), the interfering spectrum is governed not only by the design of the machine, regarded as a radio-frequency generator, but also by the electrical characteristics of the supply system. In regard to (3), the question is too general to permit of a specific reply. It is very likely, however, that variations in the character of the high-frequency portion of the spectrum will be considerably influenced by the manufacturing tolerances normal to any particular type. The variations due to supply mains could be entirely eliminated by a suitably designed mains terminating network, located between the mains and the electrical item.

Mr. Friedman's remarks on ultra-short waves and ignition systems are interesting. It is because of the difficulties which he enumerates that the recommended value of protected field strength for waves below 20 metres is as low as 10 μV per metre. Mr. Friedman's second point is covered in the reply to Mr. Kennedy.

Mr. Lett has emphasized the value of screened receivers and screened aerial transmission systems. With such means, however, complete elimination cannot be effected unless the aerial is placed outside the field of interference. In regard to the use of low-frequency cut-off, deterioration of the receiver fidelity is hardly the solution of the interference question. The quality required for satisfactory loud-speaker reproduction is vastly superior to that provided on commercial telephonic systems. The numerical example given is not very conclusive. With a static level of 100 μV per metre, as quoted, a signal/noise ratio of about 10 decibels would be obtained on a signal field of 1 mV per metre, modulated 32 per cent. Very considerable modification of the fidelity of the receiver would be required to deal with this condition.

Mr. Scroggie's remarks have been dealt with in the earlier portion of this reply. It is hoped that the figures given in the paper will thereby be made more intelligible to him.

DISCUSSION ON

"THE LOWER-VOLTAGE SECTIONS OF THE BRITISH GRID SYSTEM." *

THE AUTHOR'S REPLY TO THE DISCUSSIONS AT LONDON, NEWCASTLE, GLASGOW, BIRMINGHAM, LEEDS, LIVERPOOL, AND MANCHESTER (SEE PAGES 131–153).

Mr. C. W. Marshall (*in reply*):

London.

Mr. Kennedy is correct in assuming that only aluminium-alloy joints are painted in order to prevent corrosion. As to the relative merits of pin-type and suspension-type insulators, the advantage of the pin-type is its lower capital costs. A disadvantage is that failure of a unit necessitates its replacement before the line can be restored to service; whereas with one unit of a multi-element suspension string punctured, the line can remain in service until a convenient opportunity for replacement arises. The pin insulator has also a greater tendency to cause radio interference. Further, the allowable span lengths are smaller than with suspension insulators, thus increasing the wayleave difficulties. The small clearances between circuits of double-circuit pin-insulator lines also increase maintenance difficulties.

The line costs in the paper do not include wayleave or overhead charges; they cover construction only. The figures given in Tables 3 and 4 are contract prices for representative, and somewhat short, line sections. The lines in Cumberland, referred to by Mr. Kennedy, are relatively long and are in unusually open country, hence the lower cost per mile. The Table on page 121 was amended for the *Journal.* No special plea has been put forward on behalf of the double-busbar type of station, and it is not assumed that indoor construction must be used. It is, however, a fact that indoor busbar-type switchgear was most extensively used in the earlier grid schemes, the main reason for this being that only this type of switchgear was completely developed at the time. In later schemes, outdoor stations with a ring-type arrangement of circuit breakers have frequently been adopted where adequate site area is available. The costs given for the Guildford station do not include those for buildings. Mr. Kennedy's figure for the rupturing capacity of the Nursling 33-kV circuit breakers is too high, the nominal rating being correctly stated in the paper.

Mr. Beard's statement regarding the grading of the insulation of the 66-kV transformer windings is correct. The windings are suitable for connection to earth through a resistance or reactance. Mr. Beard is also correct in stating that hydraulic pressure tests are applied to all circuit-breaker tanks.

In reply to Dr. Dunsheath, it is impossible to give with a high degree of accuracy the maximum safe working temperatures of any type of cable. The figures in the paper provide a basis of comparison which can be used by those who operate cables, when they have determined empirically the maximum temperatures at which their cables can safely be used. The same remark holds for the I^2R losses, since their value depends on the working temperature. The sample insulators which are taken down from the lines for test are removed from spans over buildings. Only a small fraction of 1 per cent of the total number of insulators comes into this category. Complete strings are removed and sample units are tested, as indicated in the paper. So far, a more scientific criterion of quality than a comparison of the electrical and mechanical characteristics of old and new insulators has not been evolved.

Mr. Gates should note that the transformer prices quoted in the paper were not all obtained at the same time, but were spread over a period of about 4 years, during which time there were wide variations in the cost of raw materials, particularly copper. This circumstance, and the entirely unregulated competition between manufacturers, are the chief reasons for the apparently anomalous prices. Gilled-tube coolers unquestionably suffer from the disadvantage that it is more difficult to prevent their rusting than with types having smoother surfaces. This disadvantage has to be balanced against the advantage of a higher cooling efficiency. Flux densities much higher than those quoted in the paper have frequently, and apparently successfully, been used abroad. Densities of the order of 12 000 lines per cm^2 have, however, much to commend them from the standpoint of ensuring silent operation and small wave distortion. Cable terminals are usually essential because of the approach difficulties, it frequently being quite impossible to bring overhead lines directly to the transforming stations. The advantages of cables as surge absorbers are therefore to a considerable extent fortuitous.

In reply to Mr. Budgett, the standard 3° towers are square in plan. Lightning has proved a somewhat more serious hazard to operation than was anticipated, particularly with 33-kV lines. Damage to apparatus has not been extensive, but line outages are somewhat too frequent in certain districts and at some seasons of the year. Smaller towers have in some instances been erected on the ground, and the tower structure subsequently raised into position. This procedure was, however, exceptional, and the customary method of erection is to erect vertically.

As regards Mr. Frost's remarks, earth resistances of the order of 0·25 ohm or less are not uncommon for the Board's stations. There have been no accidents on the grid owing to high earth potential-gradient during faults. Separate earths are provided for outgoing low-tension networks.

* Paper by Mr. C. W. MARSHALL (see page 105).

The system of charging used for the C.E.B. batteries is what Mr. Chase has termed the "floating" method.

Mr. Bibby's suggested amendment to Table 2 has been incorporated in the final form of the paper. Fig. 5 is a remnant from a series of diagrams for which space could not be found in the printed paper. There is probably scope for a paper on overhead-line characteristics, embodying modern views on rating and stability characteristics. A battery and charging generator are available at many of the grid stations, and therefore relatively high-current d.c. tests could conveniently be arranged for short sections of line. Low-current tests have frequently been used where no suitable high-current plant is available. Table 2 has been amended, and reference to it in its final form will clear up the difficulties referred to by Mr. Bibby. The movement mentioned in the joint test is conductor elongation. Insulator tests were made specially stringent with a view to ensuring a high and uniform quality of the finished products. High-frequency tests are, or were, a recognized part of the process of eliminating unsatisfactory insulators, it being considered that a high-frequency test was more searching than the normal 50-cycle one. Insulator testing in general is now being reviewed by the British Standards Institution in co-operation with the International Electrotechnical Commission. It is not the Board's practice to install cable temperature-indicators on all cables. These are fitted only to special types of cables, the thermal characteristics of which have not been fully established in practice. Anti-flux bands have been used successfully on some high-current single-core cables at Hackney. The use of these anti-flux bands was successful in reducing to a satisfactory level a somewhat high temperature-rise of the supporting steelwork. The use of coke for earthing purposes is, to a certain extent, a haphazard matter, and there appears to be room for modification of much of this time-honoured procedure. In particular, it seems certain that in many instances no useful purpose is served by coke, which would be better eliminated. Impedance or reactance protection is used according to the type of switchgear adopted, each class of protection being associated with a particular manufacturer, or group of manufacturers. Impedance protection is relatively simple, but has theoretical disadvantages, particularly as regards neglect of arc resistance, and in the use of magnetic methods of relay timing. It has, however, given good service in practice, and, as a result, has many supporters who prefer it to the more refined and complicated reactance protection system.

The subject of cable terminations has been treated briefly in my reply to Mr. Gates. My note on the subject in the paper has been interpreted in a way which was not anticipated. It will be possible to determine the relative shielding effects of cables of different lengths on surge absorbers, and of parallel-type lightning arrestors, and so obtain a measure of the efficacy of each scheme of protection, which can be considered in relation to capital costs. The assessment of the monetary value of a failure of supply is admittedly a matter of great difficulty, and has to be considered in relation to each type of supply. Insulator-cleaning is carried out at varying intervals depending on the atmospheric conditions in the localities in which the lines and stations are situated, and also on the period of the year. In the worst cases, cleaning may be necessary every month in the winter, while lines in open country may go for years without cleaning. The use of potential-gradient indicators has been considered, but, so far, no form of live-line testing-equipment has commended itself sufficiently to the Board to justify its general adoption. The line tensions are so adjusted that the statutory clearances are maintained with temperatures up to 50° C. As the maximum current-loadings occur in winter, there is practically no possibility of clearances being encroached on because of high conductor temperature.

Mr. Le Maistre seems to be under a misapprehension as to insulator tests. The number of units tested to destruction is kept to a strict minimum compatible with ensuring that the necessary quality is maintained. Any constructive suggestions from insulator manufacturers through Mr. Le Maistre's organization would receive full and sympathetic consideration from the Board's engineers.

Mr. Duckworth is correct in stating that the 132-kV grid lines have neither duplicate insulators nor receiving bars at road crossings, and that reliance is placed on the higher factors of safety which have been provided.

Mr. Highfield has drawn attention to detail points in connection with the design of electrical apparatus for outdoor use. His observations will be of value in connection with the future maintenance and construction work of the Board.

In reply to Mr. Markwick, typical costs incurred in guarding crossings are as follows:—

Road crossing (earth bars): £3 16s. 0d. to £6 4s. 0d. per tower.
Earthing of communication lines: £33 to £138.
G.P.O. crossing (laced guarding): £146 to £386.

It is possible to undertake certain minor maintenance work on one side of the 33-kV double-circuit pin-insulator lines with the other side live. The comparatively small clearance, however, renders major operations difficult —if not impossible—in these circumstances.

The provision of quadrature control has, up to the present, not proved necessary on the grid scheme. The limitations which Mr. Young describes, however, definitely exist, and it is possible that such control will have to be provided in certain instances when the load has grown to a sufficient extent to justify the expenditure involved.

Newcastle.

Replying to Mr. Clothier, detailed information on the behaviour of apparatus under full-load conditions of working will be forthcoming in a later paper dealing with the operation of the grid. It seems certain that test-plant proof of the adequacy of circuit breakers both to make and to break their rated current will in the future be a standard requirement for all large-capacity switchgear. The life of overhead structures is purely a question of maintenance, and there is no reason why the general overhead structure should not last for 50 years, although this will inevitably involve complete, and possibly frequent, replacement of many parts as in the case of railways. The possibility of the whole of the grid over-

head system being replaced by cables is somewhat remote on technical as well as economic grounds.

In answer to Mr. Harris, all surge absorbers which have been used are of the inductance type for connection in series with the lines. There have been two cases of trouble due to lightning with lower-voltage transformers directly connected to overhead lines.

Mr. Hacking's contribution to the discussion is of a very constructive nature, and should be read in conjunction with the appropriative section of the paper. His prediction that on-load ratio control will be generally applied is rapidly proving to be correct, and such equipment is now being applied to distribution transformers of very small capacity.

As regards Mr. Ryle's remarks, the number of flashovers which have occurred is, up to the present, insufficient to enable final judgment to be made regarding the efficacy of arcing horns. Experience to date, however, indicates that these devices are distinctly beneficial in reducing the damage to conductors and insulators on the occurrence of power arcs. The decision as to when line insulators require cleaning rests on visual observation by the responsible maintenance engineers. In certain cases line-insulation testing-equipments have been installed to give a more accurate criterion, and it is possible that such devices will, in future, be more generally employed. Anti-vibration devices as used in the Board's experimental work are: Varney reinforcing rods, Bate supplementary conductors, Electrical Improvements dampers, and Stockbridge dampers. The earth resistance of towers naturally varies widely with the earth conditions. A value of 5 to 10 ohms should be taken as normal for individual towers, but resistances as low as 1 ohm have been encountered, while the maximum value recorded has been 70 ohms. When the earth wire is connected the resultant resistance is, of course, that of the whole of the earths in parallel, due allowance being made for the resistance of the earth conductor. I am in agreement with Mr. Ryle that the use of earth pipes in conjunction with steel towers is frequently superfluous, and that considerable expense may be avoided by judicious preliminary testing.

In reply to Mr. Carr, a few complaints of noise from transformers have been received from people residing in the immediate neighbourhood of transforming stations. Precautions which may be taken to reduce noise are the reduction of the flux density and the mounting of transformers on anti-vibration foundation pads. In one instance the transformer tank was completely surrounded with sound-absorbing material. This remedy, of course, is only applicable where the coolers are entirely distinct from the main transformer tank. The precautions taken by the Board to allow for expansion of connections have so far been sufficient to prevent any breakage of bushing or post insulators. I am of the opinion that the best line of development in switchgear construction is towards completely outdoor arrangements. The sizes of the transforming stations are indicated generally in the illustrations. The cost of typical purchased sites ranges from 1s. 1d. per square yard to 7s. 9d. per square yard. The relative merits of surge absorbers and lengths of cable as a means of protection against surges have not yet been clearly established. The matter is being investigated by the Surge Committee of the Electrical Research Association, the findings of which will be published when practical investigations are completed.

Glasgow.

Replying to Mr. Robertson, the use of directly connected transformers has, up to the present, proved wholly successful on the Board's lower-voltage systems. The method of connection has now been in commercial use for a period of 3 years. The Central Board has in service ratio-changing equipments of the resistance, reactance, and parallel-winding types. The experience with the equipments has been on the whole satisfactory, when it is considered that there was practically no large-scale experience available prior to the starting of the grid system. The criteria by which I would judge the relative merits of individual designs are, broadly, as follows: The ratio-changing gear should form an integral unit readily detachable from the main transformer, the speed of operation by hand should be high, and the control gear should be simple, so as to reduce the likelihood of maloperation. The grading of transformer insulation has been determined as a result of practical experience with transformers on large systems prior to the development of the grid scheme. It is largely empirical. The type of coil wire is specified only in general terms. Circuit breakers of all the best-known modern types are in service. So far there has been no serious adverse experience with any types. The oil-blast circuit breaker has the advantage of reducing the arcing period, and of minimizing the amount of oil filtration required after faults. The field operation of the breakers under fault conditions has not yet been very extensive, but the breakers have satisfactorily done the duty required of them on each occasion when line faults have occurred.

In reply to Mr. Cooper, the span lengths have been chosen with special regard to minimizing the number of wayleaves to be obtained, as this is one of the greatest difficulties encountered in connection with the erection of overhead lines in Great Britain. Any further extension of span lengths over those chosen would probably give rise to difficulties with dancing and vibrating conductors.

As regards Mr. Stronach's remarks, solid-type 66-kV cables as installed by the Board have been remarkably free from faults, and from the standpoint of simplicity have much to commend them. There are, however, commercial advantages in favour of the oil-duct and gas-pressure types which justify their subsequent adoption by the Board. The lower price of the oil-filled cable is attained by working with active materials at higher densities, and therefore reducing the total weight of material used. High-voltage direct-current tests are applied to cables only prior to going into service, or after constructional changes have been made on them. The test voltage is twice the pressure between phases, and is applied between each core and sheath. Parts of the associated switchgear, whether of the compound-filled or other type, may be subjected to the cable test-pressure. High-voltage direct-current bridge tests are frequently and successfully used for fault-location purposes.

In answer to Prof. Parker Smith's comments, the percentage-regulation values of the transformers given in

the Tables have been carefully checked and are correct. It should be noted that the transformers have relatively high inherent reactance, and that the correction factor to take account of this is large. The figures in Tables 6 and 7 have been checked against the official contract documents which are vouched for by the responsible manufacturers.

Mr. Roxburgh refers to the relative merits of suspension and pin-type insulators; these have been dealt with in my reply to Mr. Kennedy (see page 264). The choice of arcing horns rather than rings for the lower-voltage lines is largely a commercial matter. There is the further factor that the distribution of potential between the units is more uniform on lower-voltage chains than on 132-kV chains, so that there is less justification for providing rings. The question of high earth resistance arises in relatively few instances, and there the position is relieved by the fact that a high-conductivity earth wire is provided. The Board has, so far, had no adverse experiences of the type indicated by Mr. Roxburgh. The cost of line insulation is a very small percentage of the total cost of the lines, and therefore the testing costs are insignificant. It is, in fact, considered that thorough testing of the insulators will in the long run prove an economy. The cost of the only concrete-pole line erected by the Board is given in Table 4. The Board has one completely armour-clad outdoor 33-kV switchboard in service, but no outdoor gear of this type for lower voltages. The subject of cleaning of line insulators is dealt with in my reply to Mr. Bibby. The difficulty in getting lines out of service for even short periods is recognized, but the Board's practice of having duplicate supplies in practically all cases renders this possible, although sometimes inconvenient.

In reply to Mr. Pound, earth-resistance tests are made when lines are put into service and after flash-overs due to lightning have occurred. The coupling together of all earths by high-conductivity earth wires is deemed to be sufficient to ensure that no serious increase of earth resistance can arise.

Birmingham.

I would inform Mr. Coward that the development of special insulators for use in districts where industrial fog is prevalent is exercising the attention of the Board, but description of this must be deferred. The main objective is to give adequate self-cleaning surfaces so as to increase the periods between successive cleanings, and to eliminate pockets which are liable to be filled with ionized air.

In reply to Mr. Rogers, the decision to use Grade B oil was made because the Board's transformers operate at a comparatively low load factor, and therefore have low average temperatures, with a reduced tendency for the oil to sludge. The Board would not be satisfied to have only one line and transformer in service in most circumstances, as under such conditions it would not be possible to give a sufficiently high degree of reliability of supply. The question regarding new distribution authorities is outside the scope of the paper.

In answer to Dr. Garrard I would say that in the present state of the art of direct-current transmission there is, in my opinion, no immediate likelihood of its replacing the conventional a.c. schemes. The efficiency of transmission of typical 66-kV and 33-kV lines can be deduced under load conditions from the figures in the paper relating to line and transformer characteristics, with the reservation that certain additional leakage losses arise which may be considerable, particularly under adverse weather conditions. These cannot yet be accurately assessed. It is the practice of the Board to fill cone-type joints with protective compound. Liquid earthing-resistances using zinc chloride as electrolyte have a tendency to be unstable, particularly if ordinary tap water is used for filling. In my opinion the best electrolyte is sodium-carbonate solution. No standard of earth-plate resistance has been fixed, but every effort is made to ensure that ohmic values are low. Values of the order of $\frac{1}{4}$ ohm are looked on as normal for substation earths. The single-circuit-breaker station has not been in service sufficiently long to justify any dogmatic statement as to its success. So far, experience with these stations has been quite satisfactory, although it is recognized that their use involves some loss of operation flexibility and considerable complication in protective equipment. The overhead crane illustrated in Fig. 19 is installed to facilitate the erection and maintenance of the equipments, which are of very large dimensions. The value of the crane is, of course, evident principally in the erection stage. In my opinion there is insufficient justification for the wholesale installation of lightning arrestors, even on 33-kV lines. In certain areas, however, such arrestors could probably be profitably used.

Dealing with the remarks of Mr. Wilson, probably the chief factor in arriving at the decision to use steel-cored aluminium conductors was the fact that they allow of longer spans, with a consequent reduction in the number of wayleaves. Parallel-feeder protection has been used in several instances, and it is agreed that this scheme of protection has much to commend it. It suffers, however, from the serious disadvantage that subsequent tapping of lines often involves complete remodelling of the protective scheme. It is, further, too expensive in respect of switchgear for use as a standard unit system. The objection is therefore an economic rather than a technical one. Mr. Wilson's indictment of British engineers with regard to the repairing of high-voltage lines when they are live is quite unjustified. There would be no difficulty in making arrangements for such repairs, and getting men to carry them out, if necessary. It is, however, considered to be a much more satisfactory policy so to arrange the circuits that working on live lines is unnecessary. Adherence to the principle of earthing at the points of work would entirely preclude the possibility of accidents of the type described by Mr. Wilson.

Mr. Chadwick's suggestion, that surge tests would be preferable to the usual 50-cycle tests, is a logical one, and all countries engaged in high-tension development are now endeavouring to rationalize surge-testing methods.

Replying to Mr. Halton, the relative merits of pin-type and suspension-type insulators have already been dealt with. Suspension-insulator lines have advantages apart from those connected with insulation. These advantages have also been touched on. The scheme

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described by Mr. Halton for reducing the surge insulation of the lines is being considered by the Board's engineers.

While the large leading currents taken by oil-filled cables are advantageous in the sense which Mr. Buckingham describes, they also introduce quite serious operating difficulties at times of light load owing to the voltage-rise which occurs and to the low excitation on the alternators. It is, in fact, sometimes necessary to operate alternators as synchronous condensers to compensate for the effect of the leading currents in the cables.

I would inform Mr. Sumner that the railway companies have, in certain instances, made concessions with regard to the maximum spans at railway crossings, but every effort is made by the Board to ensure that the companies' requirements are rigorously met. Aluminium-steel conductors which have been taken from the Board's lines for test and examination have, up to the present, shown the steel core to be very completely and adequately protected against corrosion. In my view there is no likelihood whatever of its proving necessary, as Mr. Sumner suggests, to replace most of the existing conductors within 10 years. The Board's experience with cone-type joints has, as in Mr. Sumner's case, been very satisfactory. The anti-climbing guards consist simply of lines of barbed wire stretched between projections from the tower legs. They can readily be inspected in the field. A gate is provided at one corner of the guard to facilitate access for authorized persons.

Replying to Mr. Morton, 10 per cent is the limit of permissible voltage-drop in the event of supply being given through one line only. In my opinion it is frequently desirable to work transformers at flux densities of the order of 12 kilolines per cm^2, but it is impossible to fix a definite limit applicable in all cases.

The reasons for the apparently anomalous prices of transformers mentioned by Mr. Charley have been dealt with in reply to Prof. Parker Smith. Mr. Charley's remarks on 66-kV transformers provide a useful addendum to the paper, and I am in agreement with him as to the technical merits of Buchholz relays.

Leeds.

The conductor to which Mr. Siviour refers is a special earth conductor. The outer conductors are aluminium and not copper as suggested in his contribution to the discussion. The flash-over values of insulator strings are taken with the arcing horns in position as in service. The testing of insulators with the lines in service has been considered, but has so far not been adopted in normal maintenance work. The concrete-pole construction, although likely to have lower maintenance charges, suffers from the disadvantages that the poles are extremely heavy and their transport is liable to cause difficulties and damage to property. The poles are also inflexible as regards their length; this introduces difficulties when an increase in the height of the line is necessitated by building operations. These remarks, of course, hold only for the heavy high-power lines such as are used by the Board. The disadvantages of concrete poles may disappear entirely for other classes of lines. The Board are using 33-kV cables of both the H and the S.L. type. In my opinion it is not yet possible to state categorically in general terms the limits of the working voltage and power factor for high-voltage cables. The criteria for determining the stability of cable dielectrics are still controversial matters, and reference must be made to specialized papers on cable characteristics for information regarding them. The oil-filled cables on the Board's system have been free from major faults. Oil leaks have from time to time occurred, but have been eliminated by replacement of defective sections. Recent experience seems to confirm Mr. Siviour's contention that the current rating of the 33-kV solid-type cables is somewhat conservative. Dr. Dunsheath's contribution to the London discussion indicates the views of a cable manufacturer on this point. Mr. Siviour's assumptions regarding the costs given in Tables 4 and 5 are correct. The line insulation as originally designed was uniform, and no co-ordination in the American sense of the term has yet been adopted. I am interested in Mr. Siviour's opinion that the benefit resulting from the use of cable terminations as protection against lightning has been over-estimated, and consider that a quantitative statement from Mr. Siviour supporting his view would be of great value.

In answer to Mr. Shuttleworth I would state that the use of steel-cored aluminium conductors has so far proved satisfactory. It is, however, essential to pay great attention to details of the joints in order to ensure trouble-free operation. Regarding the practice of reinforcing conductors and insulators at crossings, my experience suggests that duplication of the conductors is superfluous. All lower-voltage line crossings on the C.E.B. system are, however, made in accordance with Electricity Commissioners' Regulations. Induction troubles on railway and Post Office communication lines are avoided by ensuring that the mutual inductance between the Board's lines and the communication lines in question is as low as possible. So far, in normal operation the Board's lines have given rise to no inductive interference with properly installed and maintained communication lines. The practice of running an earth wire at the apexes of towers as a protection against lightning is justified on the basis of the theoretical and experimental investigations carried out in America by the late Mr. F. W. Peek. The Board's experience with compression-type joints is relatively small compared with its experience with cone types. The compression joint has the disadvantage that it requires special field equipment, and that it produces a somewhat indefinite degree of damage to the conductor sections which it joins. When a well-manufactured and well-designed conductor is employed the danger of moisture getting through the outer aluminium strands appears to be remote. The pin-type insulators used in South Scotland were, as stated in the paper, adopted purely for economic reasons. For 33-kV copper lines of small cross-section it is probable that pin-type insulators would be quite satisfactory in most instances; but for larger lines, and particularly where the atmospheric conditions are liable to give rise to corona discharge and consequent radio interference, I would prefer to use suspension insulators. My experience with Pyrex insulators has been confined to a few sample units. The type tests on these units were satisfactory, and technically they appear to be quite able

to compete with porcelain. So far, there have been only a few cases of wilful damage to the Board's insulators. In one or two instances insulators have been damaged by rifle fire, but in no case has service been affected. In the design of suspension clamps the principal points which have to be taken care of to ensure satisfactory service are axial suspension and mobility—so as to allow transference of vibration without local stressing of the aluminium. It is also important to ensure proper bell-mouthing of the clamps, which should be as light as possible. Vibration troubles have occurred in a few instances owing to excessive tension of the conductors; the difficulty has been eliminated by correcting this, or by the addition of Stockbridge dampers where it was not practicable to relieve the tension. Concrete poles have so far proved satisfactory, except in the respects mentioned in the reply to Mr. Siviour. The reason for the anomalous costs of conductor to which Mr. Shuttleworth refers, lies in the fluctuations of the cost of basic materials. The gas-pressure type of cable was installed largely as an experimental measure, and its cost to the Board was the same as that of a normal solid-type cable. The performance of this cable has so far been perfectly satisfactory. Gas leaks occurred at first which were somewhat difficult to locate and repair, but these leaks have now been eliminated.

The decision not to fit on-load ratio-changing gear to transformers of 2 000 kVA capacity or less was arrived at largely on account of cost. Hand regulation is normally used, but in one or two special instances automatic equipment has been installed. Regarding the system lay-out, single supplies have been adopted in certain instances on economic grounds, but the ultimate form of the grid scheme provides for duplication of all supplies. The copper earthing connections are considered by the Board's engineers to be adequate both mechanically and electrically. Where ground conditions make it necessary the strips are bitumenized to prevent corrosion. Liquid resistances have proved quite satisfactory; the main reasons for their adoption were then very much lower cost, greater flexibility, and compactness, compared with metallic resistances. They are quite suitable for use on any voltage, and are extensively employed on 11-kV and 6·6-kV systems. All are provided with heating elements to prevent freezing. The choice of electrolyte is important if it is essential that the resistances should maintain constant ohmic values. The experience of the Board with outdoor 66-kV metalclad switchgear is somewhat limited, but up to the present it has been satisfactory.

In reply to Mr. Field, the choice of star/delta transformers is based on the better mechanical and electrical properties of this type compared with the star/star type with tertiary winding. Unless the tertiary winding is of robust construction and high capacity, it introduces a serious weakness, and alternatively increases the cost of the transformer. The advantages of the star/star connection from the standpoint of simplicity in phasing and earthing are, of course, evident, but it is considered that these advantages do not compensate for the above-mentioned drawbacks. The need for a more comprehensive definition of the characteristics of tertiary windings is, as pointed out by Mr. Field, very desirable. This matter should be referred to the appropriate committee of the British Standards Institution. The Table on page 121 originally contained certain errors. These were eliminated before the paper appeared in the *Journal.*

Dealing with the question raised by Mr. Hinings, in most circumstances the use of tertiary windings in star/star transformers is essential for the elimination of third harmonics; but in some special cases, e.g. in works distribution, the tertiary winding can safely be omitted.

Mr. Hedley's opinion that the flux densities given in Table 7 are excessive is not shared by other engineers, who have expressed diametrically opposite opinions. The ratios of load losses to fixed losses were chosen to suit the load conditions under which the lower-voltage transformers operate in each particular case.

The figures in Table 1 to which Mr. Longman refers are presumably those in columns (*b*). These were obtained from the well-known circle-diagram theory for short transmission lines. The items (*a*), (*b*), and (*c*), in column 1 of page 110 represent arbitrary assumptions for conditions in which the temperature-rise of conductors can be calculated from first principles, or where well-authenticated empirical figures exist. Regarding power-line crossings, the second comers should, in equity, pay for any protection which is required by the regulations. The upper limit of the temperature-cycle tests has been fixed as a result of conferences between both the insulator users and the manufacturers, and it is unlikely that agreement would be reached to adopt the upper temperature of 90° C. suggested by Mr. Longman. In some instances, however, this temperature has been used in the past.

Liverpool.

In reply to Mr. Paton, the Board endeavour to keep the number of joints in spans to a minimum, and especially to avoid joints in spans at crossings of roads, railways, and buildings. It is, however, economically impossible to avoid such joints entirely. Up to the present, their use has not been attended with any ill effects. With regard to suspension-insulator hooks, care must be taken to ensure that such fittings do not readily unhook when the insulator chains are subjected to upward thrust such as occurs when snow loading is released. To eliminate this risk it is, with some designs, advisable to fit a locking device at the mouth of the hook. Hill-side extensions must be designed specially for each particular case. It was not practicable to illustrate such details in the paper owing to space exigencies. The cost items mentioned by Mr. Paton are not covered in Tables 4 and 5. The reasons for the anomalous costs have already been dealt with in the reply to Mr. Gates. I suggest that the technical particulars and the weights provide a sufficient basis for giving an equitable idea of what the costs would have been in more stable conditions of prices of basic materials, and in the absence of uncontrolled competition. It was not my intention to suggest that the primary purpose of earth wires is for lightning protection. I agree with Mr. Paton that they are primarily used for earthing purposes. The total circuit mileage of 132-kV lines on the grid system is approximately 3 770.

The practice of casing the tower legs with concrete,

mentioned by Mr. J. A. Morton, unquestionably protects the steelwork up to the junction of the concrete and steel, and it is comparatively easy to maintain this admittedly vulnerable point by bitumenizing. The main point is to ensure that the stubs themselves will be as nearly as possible permanent. The cost of cables does not include concrete covers, trenching, and permanent reinstatement. I agree with Mr. Morton that fine sifted soil is in many circumstances better than coke. It is particularly desirable to prevent the coke from coming in contact with the copper connections between the earth pipes and structural work. Driven rods in parallel have also definite advantages, but their use is frequently not practicable owing to the presence of rock. I agree that the Electrical Research Association's report on earthing should be of distinct value to overhead-line engineers.

In reply to Mr. Swift's inquiry I would state that the capacities of the overhead lines have been chosen with reference to the anticipated demands in the districts which they supply. Ageing of cement in insulators has so far caused no trouble on the grid system. It must, however, be remembered that the critical period in this respect is somewhat over 5 years, and the oldest grid lines are only approaching this age. Cemented and metallic fixings have both been used on the grid insulators. There has up to the present been only one case of bird trouble on the grid lower-voltage lines. This was due to a large owl causing a fault to earth on a 33-kV pin-insulator line. Reconditioning of transformer oil is done with the transformers dead. Under the lock-in protective system, sound sections remain unprotected while a faulty section is being cleared. The occurrence of a fault on a locked section would, however, render the protective equipment operative. Further, the back-up overload protection remains as a final safeguard.

Replying to Mr. Bull, the time of clearance of a line which has been earthed depends on the type of protective equipment used. With balanced protective equipments of the Merz-Price class the relays operate in approximately 0·1 sec., while with distance or lock-in protection the time of relay operation is of the order of 1 sec. To these times must be added the time of clearance of the circuit breakers: this varies with their type from, say, 0·2 sec. to 0·5 sec.

I would inform Mr. Stirrup that, as is indicated in the reply to Mr. Young, quadrature regulators have not yet been used by the Board. It is possible that such devices may be required in the future. Reactors both of the indoor concrete type and of the oil-filled type have been used, the type chosen depending largely on the lay-outs of the stations in which they are used. These stations being the property of authorized undertakings, consideration has to be given to the requirements of their responsible engineers. The extension of standard span lengths up to 35 per cent is done without encroaching on the factor of safety of the lines. The 0·06-sq.in. S.C.A. conductor is used as an earth wire on a long-span 66-kV section. The costs given in Table 4 include expenditure on erection. The items which are not particularly specified include special steelwork for extensions and guards, which in some lines form a somewhat large percentage of the total cost. In cases where solid tappings are used the primary windings of the tapping transformers come into the zone of protection of the lines, and in the event of their failure the whole line section is disconnected by leakage protective gear.

Mr. Bunn asks the reason for the adoption of arcing horns. These have been provided on the Board's 66-kV and 33-kV lines with a view to reducing damage to conductors and insulators on the occurrence of line faults. The relatively high short-circuit powers on the grid system give further justification for their use in contrast to smaller systems where the power available is more limited. Regarding Mr. Bunn's opinion that a lower slipping force than that specified by the Board would have been advisable in view of the extra protection afforded to the towers, experience up to the present, which includes one case of an aeroplane flying into a line, does not suggest that the grid towers would be liable to serious damage in the event of conductor breakage.

In answer to Mr. Holtum's inquiry, the cost figures in the last line of Table 5 are for one circuit per trench. They do not include the cost of excavation.

In reply to Mr. Livesey, multiple earthing of the neutral points of systems is forbidden by the Regulations, and provision for multiple earthing such as was used on the Board's 132-kV system can only be obtained by special dispensation from the Electricity Commissioners, and by arrangement with the Post Office.

Mr. Livesey's assumption that high-voltage tests are applied also to outdoor switchgear is correct.

Mr. Bellamy inquires as to the usual method of climbing concrete poles. Repairs to and cleaning of insulators on the Brighton–Worthing concrete-pole line involve the use of portable ladders. This is a definite disadvantage of the construction. Mr. Bellamy's point regarding the maintenance of pin-insulator 33-kV lines has been dealt with in the reply to Mr. Markwick. Wherever possible the Post Office provide underground pilots for the interlocking protective equipments. Where overhead pilots are provided they undoubtedly constitute an additional hazard.

Replying to Mr. McKenna, the reason why only one line was erected on reinforced concrete supports has been dealt with in the reply to Mr. Siviour. The basic prices of the materials mentioned in Tables 2, 4, and 5, are approximately as shown in Tables A, B, and C respectively. With regard to the costs of conductors, Mr. McKenna should note that these include allowances for erection, and the expenditure on the individual contracts has an important bearing on this factor. The vibration troubles are, as anticipated by Mr. McKenna, dealt with as they occur. It would be quite uneconomic to fit anti-vibration devices generally, or, alternatively, to reduce the conductor tensions throughout to such an extent as to preclude vibration. The special problems relating to insulation of the lines are being dealt with on similar lines, and for the same reasons.

Manchester.

In reply to Mr. Fennell, the voltage drop on the various sections of the system is dealt with by hand adjustment of the on-load ratio-changing equipment at the supply and delivery ends. The regulating equipment is an integral part of the Board's transformers. The ageing

TABLE A.

Line and Earth Conductors (see Table 2).

Date of contract	Nov. 1931	March 1931	Oct. 1929	Dec. 1930	Jan. 1931	March 1931	Aug. 1931	May 1929
Material of conductor	S.C.A.	S.C.A.	S.C.A.	S.C.A.	S.C.A.	Locked-coil S.C.A.	S.C.A.	Copper
Nominal section (copper equivalent), sq. in.	0·05	0·06	0·075	0·10	0·15	0·15	0·175	0·10
Basic materials Cost (maximum)	£ s. d.	£ s. d.	£ s. d.	£ s. d.	£ s. d.	£ s. d.	£ s. d.	£ s. d.
Steel angles	8 7 6	8 7 6	8 2 6	8 7 6	8 7 6	8 7 6	8 7 6	8 2 6
Aluminium	95 0 0	85 0 0	96 0 0	85 0 0	85 0 0	85 0 0	85 0 0	96 0 0
Electrolytic copper bars	45 15 0	50 12 6	84 15 0	56 10 0	49 15 0	50 12 6	37 0 0	85 0 0

TABLE B.

Typical Costs of Overhead Lines (see Table 4).

Date of contract	March 1931	March 1931	Aug. 1931	Dec. 1930	Oct. 1929	May 1929	Aug. 1931	Oct. 1932	Aug. 1931	Dec. 1930	Aug. 1931	Oct. 1932	Nov. 1931
Type of line	66-kV double-circuit		33-kV double-circuit						33-kV single-circuit				11-kV single-circuit
Conductor section, sq. in.	0·15	0·10	0·175	0·1	0·1	0·1	0·075	0·075	0·175	0·1	0·075	0·075	0·05
Conductor material	S.C.A.	S.C.A.	S.C.A.	S.C.A.	Cu	Cu*	S.C.A.	S.C.A.	S.C.A.	S.C.A.	S.C.A.	S.C.A.	S.C.A.
Basic materials Cost (maximum)	£ s. d.	£ s. d.	£ s. d.	£ s. d.	£ s. d.	£ s. d.	£ s. d.	£ s. d.	£ s. d.	£ s. d.	£ s. d.	£ s. d.	£ s. d.
Steel angles	8 7 6	8 7 6	8 7 6	8 7 6	8 2 6	8 2 6	8 7 6	8 7 6	8 7 6	8 7 6	8 2 6	8 7 6	8 7 6
Aluminium	85 0 0	85 0 0	85 0 0	85 0 0	96 0 0	96 0 0	85 0 0	80 0 0	85 0 0	85 0 0	85 0 0	80 0 0	95 0 0
Electrolytic copper bars	50 12 6	50 12 6	37 0 0	56 10 0	84 15 0	85 0 0	37 0 0	39 10 0	37 0 0	56 10 0	37 0 0	39 10 0	45 15 0

* Line with concrete-pole supports and steel earth wire.

TABLE C.

Cables (see Table 5).

Date of contract	June 1929	June 1929	June 1929	July 1929	July 1929	July 1929	Sept. 1931	Oct. 1930	June 1929	Sept. 1930
Voltage	66-kV							33-kV		
Type of cable	$S.C._1$	$S.C._1$	$S.C._1$	O_1	O_1	O_1	O_3	$S.C._3$	$S.C._3$	$S.C._3$
Sectional area of conductor, sq. in.	0·15	0·25	0·35	0·15	0·25	0·35	0·15	0·15	0·25	0·30
Basic materials Cost (maximum)	£ s. d.	£ s. d.	£ s. d.	£ s. d.	£ s. d.	£ s. d.	£ s. d.	£ s. d.	£ s. d.	£ s. d.
Electrolytic copper bars	84 15 0	84 15 0	84 15 0	84 15 0	84 15 0	84 15 0	44 0 0	47 10 0	84 15 0	51 10 0
Lead	25 5 0	25 5 0	25 5 0	24 15 0	24 15 0	24 15 0	17 0 0	18 0 0	25 5 0	19 10 0

$S.C._1$ = solid cable, single-core. $S.C._3$ = solid cable, 3-core. O_1 = oil-filled cable, single-core. O_3 = oil-filled cable, 3-core.

of insulators has been dealt with in the reply to Mr. Swift, and the cleaning of insulators in reply to Mr. Bibby. The winding temperature of transformers is obtained by what may be termed a compound thermometer, the registrations of which depend on the oil temperature and on the current in the windings. One method of carrying out this principle is to surround the bulb of the thermometer by a coil, the temperature of which changes with the temperature of the hottest spot in the windings.

Dealing with Mr. Kidd's contribution, the reactor schemes adopted have been determined primarily by the arrangement of the switchgear in the stations of authorized undertakings. The advantages of the star-connected reactor system are fully recognized, and the system has been used in many instances on the grid. The range of ratio-change available at the supply and delivery ends of the Board's lower-voltage lines is such that the allowable upper limit of voltage asked for by the authorized undertakers is not exceeded. The various ranges of ratio-changing equipments are given in the paper. Temperature indicators are provided on the Board's transformers to give the oil temperature and the highest temperature of the windings. In unattended stations the winding-temperature thermometers are used for disconnecting the transformers directly, but in attended stations they merely give an alarm and it is left to the operating staff to disconnect the transformer. The matter of earthing pipes has been dealt with in the reply to Mr. J. A. Morton. Induction densities in transformers have been dealt with in the reply to Mr. Gates. Remote control of switchgear has been adopted quite extensively where its use is economically justifiable. Instances of such equipment are the control of Hebburn switching station from Carville power station, of Osbaldwick switching station from York power station, and of Rayleigh switching station from Barking power station. It is not improbable that this type of control will be extended to other stations in the future.

Mr. Davey makes an interesting commentary on high-voltage cable performance and development. I agree with him that if it proves possible to return to the simplicity of the older form of solid cable, and at the same time to give the undoubted advantage of freedom from electrical breakdown which has been the feature of the oil-filled and pressure-type cables, a considerable step forward in cable technique will have been made.

The need for adequate rupturing-capacity tests on circuit breakers, mentioned by Mr. Ferguson, will not be contested by anyone concerned with this branch of electrical engineering. The switchgear manufacturers in this country are somewhat tardily providing the necessary equipment, and experience should soon be available to determine more definitely what are the necessary and sufficient tests to apply to all classes of circuit breakers to ensure perfect operation in service.

Mr. Burnett's contribution regarding protection of equipment against lightning is of considerable interest. The value of good modern fuses in maintaining general supplies by disconnecting branch circuits without operating main circuits has frequently been advanced by advocates of fuses. The Board's experience with directly-connected transformers, which includes installations in areas subject to frequent lightning storms, is not such as to cause it to consider the adoption of fuse protection, except possibly for very small transformers.

I would inform Mr. Howarth that where supply undertakings have transformers of 2 000 kVA or less, the regulation is done from the transformers at the supply end, or by local regulating equipment which is the property of the undertaking. The capacity of the tertiary windings on the Board's transformers is not considered to be excessive in view of the earth-fault conditions to which the transformers may be subjected. The subject of neutral earthing has been dealt with in reply to Mr. Livesey.

In reply to Messrs. Bell, Arnett, and Sills, I have a definite personal preference for the practice of enclosing transformer terminals as far as is economically practicable.

Replying to Mr. Hardman, the impedance voltages of the Board's transformers have been chosen after consultation with the principal transformer designers, and are the lowest values which could be adopted while meeting the specification requirement that the transformers shall be able to withstand a dead short-circuit on their terminals with full voltage maintained on the windings. This requirement applies to all transformers without making any allowance for line impedance.

Mr. Larcombe mentions the use of wooden poles. This was carefully considered by the Board, but it was decided that the best policy for the country as a whole was to adopt lattice steel towers as standard construction. In this connection it should be recognized that the Board's lines are of very much larger capacity and therefore of heavier construction than is normally used, and that long spans were an essential requirement in view of the great difficulties of obtaining wayleaves in this country. The earthing of the Board's 11-kV lines is in accordance with the Commissioners' Regulations, which give the alternatives of providing a continuous earth wire or of earthing the metalwork at individual poles.

In reply to Mr. Melling, it is recognized that there are situations in which it may prove necessary to reinforce the insulation of the Board's lines because of local atmospheric pollution. The extent of the lines to be reinforced and the amount by which the insulation must be increased can, however, only be determined by experience. Frequency of cleaning of insulators has been dealt with in the reply to Mr. Bibby. The cost of cleaning is approximately from 1·5d. to 2·7d. per insulator unit.

DISCUSSION ON

"ELECTRICAL METHODS OF GEOPHYSICAL PROSPECTING."*

EAST MIDLAND SUB-CENTRE, AT DERBY, 24TH OCTOBER, 1933.

Dr. W. A. Richardson: I am a geologist, and therefore the new methods of prospecting which have sprung up during the last few years are of more than usual interest to me. One realizes the real advantage of these new methods when one considers what the mining engineer and the geologist had to depend upon in the old days. For instance, in order to determine the value of a mineral concession or an oil field, a geologist had to seek information in chance exposures, piece this together, and, when this surface information had been reduced to some order, he had to use what imagination and knowledge he possessed to trace the underground structure. Even if some surface evidence is present and sufficient time is available to find it, and assuming that knowledge and inspiration to interpret it are at hand, the problem is still difficult and costly. Such methods of exploration will obviously be slow and the results late in coming. Here is one of the outstanding cases where two branches of science have co-operated, to the advancement of knowledge and the benefit of the community. Let me give one or two instances of the use of geophysical prospecting. In 1923 a Frenchman named Lasareff discovered by a magnetic survey a mass of magnetite completely hidden below the surface, which was later proved at a depth of 150 metres. In the United States, similar magnetic methods enabled the function between a bed of quartzite and one of slate covered by a mass of glacial debris to be traced. In Canada the Alty brothers in 1930 used electrical methods for detecting salt. Salt occurs there in big plug-like masses, often completely hidden. The water in the salt mass is more highly concentrated than the solution outside, with corresponding effects in electrical conductivity. Apparently electrical methods enable salt domes to be detected at a depth of 600 metres; other methods give equally interesting results. For instance, one may create a local earthquake by producing a small explosion, and by seismographs detect at various places the emergence of waves caused by the shock. When a wave of this kind meets a discontinuity such as the junction of two different layers, it is reflected like light at a mirror. The depth at which the wave is reflected can be calculated from the time of transit and the angle of its emergence. This method is the only one which will give the depth with any certainty. Heiland in 1933 claimed that he could detect the presence of a reflecting layer within 2 metres at a depth of 1 000 metres. There are various geophysical methods, the choice of which depends upon the circumstances in which they are to be applied. The Anglo-Persian Oil Co. have been able to trace hidden folds by gravitational methods, an important matter for an oil company, which can thus develop its field scientifically and economically. A paper by Koenigsburger of Freiberg (1933) deals with the search for water and illustrates the efficiency of combined methods. He recommends firstly a preliminary geological survey; secondly, an exploration of the water body by means of the 4-electrode method, or, if it lies below a depth of 200 ft., by means of the central induction method; and lastly, after this exploration he recommends the use of seismic methods for ascertaining the exact depth of the water-bearing stratum. The interesting point here is that complete information is to be obtained only by a combination of various methods, and such use would in the end probably save much waste of capital expenditure. The question occurs to me, why were these methods not applied earlier? Ever since the year 1845, when Pratt discovered the anomalous behaviour of the plumb-line near mountains, gravitation methods have been regularly used by surveyors and have yielded much information about the mechanics of mountain building. Moreover, ever since the compass was first used in mine surveying, the effects of local attraction due to the varying magnetic effects of different rocks have been known. Yet it is little more than a decade since such "geophysical" properties were applied to problems of geological surveying.

Dr. A. Bramley: Nowadays we hear so much about electron physics and X-rays that we are liable to overlook the fact that other developments in physics are taking place at the same time. I feel that much of this other work is of more importance from an economic point of view than the progress in electron physics. The author's reference to anthracite and graphite giving rise to differences of potential reminded me of the old problem of whether we might use coal as an electrode and obtain the energy directly in the form of electricity. The paper has brought very forcibly to my mind the importance of a wide survey of science, and the great necessity for the modern student of science not to be too narrow in his training and outlook. Thirty years ago one would never have thought of this sort of work being applied to mining. When I was in Sweden a few years ago I saw an example of a survey which had been carried out in connection with some of their famous iron mines. Although mining has been carried on in Sweden for 800 years, it was thought worth while to make an extensive geophysical survey. We talk of town planning; in Sweden they have planned their country, and have decided upon the best places to locate their workpeople, buildings, and railways. Ultimately they will effect a tremendous saving through knowing exactly where their ore lies and which is the best way to work it.

Mr. C. A. Brearley: Will the author state whether, in the spontaneous-polarization method, the results obtained vary according to the time of observation—

* Paper by Mr. J. M. BRUCKSHAW (see vol. 73, p. 521).

day or night, or the seasonal period? Referring to Fig. 6, in most regions lines of equal conductivity conform roughly to the contour lines, but at Red Hill Farm they are roughly perpendicular to them; is there any special reason for this, e.g. the direction of the line joining the electrodes? May I also ask whether there is any scientific support for the "hazel-twig" and similar methods of divination?

Mr. M. H. Simpson: I have wondered whether the electrical resistance methods are of much service in prospecting for oil. In this connection it would be of interest to know whether the capacitance effect has been employed by measuring leading out-of-phase current when exploring the neighbourhood for oil, without locating more easily-found substances such as salt, which I believe is also found in neighbourhoods where oil is present.

Mr. J. M. Bruckshaw (*in reply*): Dr. Richardson states that the Anglo-Persian Oil Co. have obtained much useful information by the use of the gravimetric method. This method has, however, now been superseded by the seismic method, and, apart from the results of economic importance, the work has resulted in a great advance in the theoretical side as well as a new field seismograph of increased sensitivity due to J. H. Jones. The main reason for the apparent delay in the application of the gravimetric and magnetic principles to the elucidation of geological problems was the time taken to develop a suitable field technique, together with the necessary reliable, robust yet sensitive field instruments. Until these problems had been satisfactorily solved the slow rate of working and the cost would outweigh the advantages gained. The deviation of the plumb line and, even now, of the most accurate and sensitive pendulum, is too crude for geophysical work, while modern magnetic instruments measure changes to the nearest 3×10^{-5} or 4×10^{-5} gauss, equivalent to a change in the horizontal component of the earth's magnetic field of 1 part in 6 000.

In the spontaneous-polarization method there is definitely a seasonal variation in the activity of a polarizing body, the variation being attributed to the fluctuation of the water horizon. I do not think that any diurnal variation has been noticed, although a fall of rain may modify the results obtained to some extent. The disagreement between the lines of equal conductivity and the true subsurface contours in the survey at Red Hill may be due to some extent to the direction of the line of the electrodes, to small variations in the resistivity of the overburden, and, to a less extent, to the resistivity of the limestone itself. Another point is that the shape of the resistivity curve for any general interface cannot be calculated, and the method consists of obtaining the depth of a horizontal interface which, using the same resistivities of overburden and underlying formation, gives the measured apparent resistivity for the electrode separation used. It is assumed that this depth is an approximation to the mean depth of the true surface. It is obvious that with mild topography the result will be a close approximation, the factor involved being the percentage variation in the true depth over the electrode separation used. Near an outcrop, as at Red Hill Farm, this variation will be large and will also depend on the relative direction of the electrode line.

There has been no extensive scientific investigation of the divining rod, and certainly no satisfactory theory has been advanced to explain the phenomenon. Opinion is divided, but there seem to be well-authenticated cases in which the divining rod has been successful. Whether the results are due to an appreciation, either conscious or subconscious, of the local geology on the part of the diviner, or whether it is due to some unknown reaction, seems open to question.

Resistivity methods have been used on several occasions in the search for oil to depths of about 100 metres, but at greater depths other methods are employed. Some work on the question of the effect of the dielectric constant on the distribution of alternating current has been done by Dr. Smith-Rose at the National Physical Laboratory.* The effect of the dielectric constant (κ) depends on the magnitude of the term $2\sigma/(\kappa f)$, where σ is the conductivity in electrostatic units and f the frequency. If this is much greater than unity the dielectric constant has a negligible effect. By direct measurement of κ and σ at different frequencies for surface soils in the neighbourhood of Slough, he has shown that below 10^6 cycles per sec. the effect may be ignored. Consequently, it is hardly probable that the dielectric constant of a thin oil-bearing formation about 1 000 ft. deep would produce leading out-of-phase components at the surface of sufficient magnitude to be detected when frequencies of the range 20–500 cycles per sec. are employed.

* *Proceedings of the Royal Society*, A, 1933, vol. 140, p. 359.

DISCUSSION ON

"THE RELATIVE FUEL ECONOMY OF ELECTRICITY, GAS, OIL, AND SOLID FUEL, AS HEATING AGENTS." *

AT BRISBANE: AT A MEETING ARRANGED BY THE QUEENSLAND LOCAL COMMITTEE, 11TH AUGUST, 1933.

Mr. A. Uscinski (who read an abstract of the paper): Very many factors have to be taken into consideration when comparing the relative values of electricity, gas, oil, and solid fuel, as heating agents, whether for industrial heating or for the heating of buildings. The cost of electricity invariably appears to be high; but when the losses and labour costs which are unavoidable with other heating agents are taken into consideration, electricity often proves less expensive, apart from its many advantages, which cannot readily be assessed in money value and are consequently very often overlooked. Electrical energy is, in effect, merely heat, and by its agency heat can be delivered through small flexible wires to any desired accessible point in any quantity, at any temperature, and in any desired form (radiant, luminous, or non-luminous of any desired wavelength), without any labour, trouble, or difficulty. Electricity for power and lighting must be available whenever it is required, so that expensive machinery has to be kept in operation 24 hours per day in order to meet the varying demand, which is very low between 11 p.m. and 6 a.m. It is possible, however, to make full use of the generating plant by storing the energy, during the "off peak" hours, in the form of heat in storage stoves, and by heating water to be used during the day. Electric storage stoves are being extensively used on the Continent and in England. They have proved ideal from the consumer's point of view because they are always ready for use at full heat and their running costs are low, and from the supply authority's point of view because they take energy at a time when it is not required for other purposes.

Mr. F. R. L'Estrange: The heating of buildings is not common practice in Queensland, but the details given in the paper are very valuable to those dealing with heating matters. In most cases cost is not the determining factor, as a certain convenience value must be allowed for. It would appear that for domestic purposes the convenience value of electricity is equal to the total energy cost; electricity should therefore have no competitor. To illustrate the convenience value the following may be cited:—

(*a*) Wiring points from which radiators can be used will also, when desired and without any alteration, supply current to other domestic appliances.

(*b*) The appliance can be moved from one part of the house to another, the heat or convenience can be obtained exactly where it is required, there is no risk of fire, no smoke, smell, or fumes, no attention is necessary, and every appliance is portable, efficient, and free from noise.

(*c*) The convenience and saving in cost by not having to clean flues, repaint walls, remove residue, etc.

(*d*) The complete elimination of process spoiling by using electricity for heating, particularly in the drying of printed tin plate and combustible material, the melting of metals, baking of bread, etc.

When discussing the question of industrial heating, the cost of electrical energy as compared with that of other heating agents has to be considered, but a convenience value must also be taken into account. The combustion losses shown by the author are particularly interesting. It would be of great value to have details of the comparative losses at higher temperatures, as the application of a blower to increase the temperature with certain fuels must have some effect, possibly in the direction of favouring electricity. On account of the totally different temperature conditions existing in Queensland, the figures given in the paper and in the discussions in Great Britain cannot be strictly applied in Queensland. In water heating, our minimum temperatures are higher, the Brisbane average being approximately 14 degrees F. above that of Great Britain.

Mr. H. B. Marks: The object aimed at in every form of heating under discussion is to give a comfortable sense of warmth to the occupants of the rooms of a building, which may be an office or workshop, a schoolroom, a church, a public room, a hall, a theatre, a living room, or a bedroom; and the requirements in every case differ very greatly. Comfortable temperatures vary widely for the different methods of heating. The use of radiant heat from a high-temperature source means that the clothing of the occupants of the room will absorb the heat energy and, consequently, will rise in temperature, thus creating a condition of comfort in air which would otherwise be decidedly chilly. Whereas if the temperature of the air in the room be raised as a whole, in order to attain a comfortable temperature of 60° to 65° F., it is obvious that very much more heat energy is required in order to obtain such an air temperature, and also to provide for greater heat losses to the walls of the room and allow for sufficient ventilation. When the advantages of electrical means of heating are balanced against its cost the result undoubtedly favours the use of this form of heating. There appears to be a great future for the heat pump. Low-grade heat can be produced at efficiencies apparently over 100 per cent, depending on the initial and final water temperatures; and by using this method in combination with a water-storage system a very economical method of heat production could be evolved. The heat pump alone is essentially a reversed refrigerator. By the alteration of a few valves, to change over the hot-water and cold-water sections, it can be made a refrigerator, or, at least, a cold-water machine. This offers an opportunity of using the machine throughout the year, as a cooling medium during our 7-months' summer and as a heating medium during the other 5

* Paper by Mr. A. H. BARKER (see vol. 72, p. 269).

months. A central heating and a central cooling system based on these lines should prove very valuable in hotels, theatres, etc., and might even be adopted in some offices. It should also be of great use in domestic establishments. It appears from the paper that the thermal-storage system is very much favoured in preference to local electric heating. There seem to be several arguments in favour of this system, two of which are: (1) By means of thermal storage it can be arranged to use electrical energy at "off-peak" periods. Any electric supply authority would welcome such a load and would supply it at the cheapest possible rate. (2) Such a heating system could be readily combined with the ordinary hot-water system of an establishment.

Mr. H. D. Ahern: One method of building-heating not mentioned by the author, but apparently ideal for Australian requirements and particularly for Queensland, is the unit heater. This consists of a number of space heaters mounted in a metal box and operated in front of an electric fan, the blades of which are specially designed to give good distribution of the heated air. The unit heater can be located in the walls, on the floor, or at any desirable point, is low in first cost, is highly efficient, and can be arranged to tone with the room surroundings.

Mr. W. M. L'Estrange: One of the outstanding problems in connection with our climate in Queensland, where in winter we have long periods of dry, cold, westerly winds, is the matter of "ideal comfort conditions." With such a wind and a temperature of 58° F. the conditions are uncomfortable. In a climate such as that of Brisbane the conditioning of air, either by heating, cooling, or moistening, is of the utmost importance, and the ventilation of our modern theatres with conditioned air indicates that in the future all large buildings must be so treated. In view of the low cost of electricity for long-hour users, it is not unreasonable to expect that, in the near future, where electricity is available from large power stations, selected rooms in our private houses, both in the city and in the country, will be made comfortable under all atmospheric conditions. Mention has been made of the storage of heat in water and metals, and it is much to be regretted that, in the past, this method has failed owing to suppliers of, say, continuous water heaters under-estimating the demand for hot water in individual households. Because the demand for these storage heaters has been small, the cost has been higher than would be necessary if every household which is supplied at the present time with electricity for heating purposes were to purchase one of these heaters. It is unquestionable that such a heater of adequate capacity, with electrical energy at the price mentioned by Mr. Uscinski in his review of the paper, would provide both a cheap supply of hot water and a supply under conditions which would compare favourably with any other method at present in vogue.

DISCUSSION ON "TELEVISION WITH CATHODE-RAY TUBES."*

Dr. V. Babits (Budapest) (*communicated*): The author says on page 440 that if the number of picture elements be taken as 70 000, then "the net theoretical gain of the mosaic system compared with the conventional system of television is 70 000 times." Further, he remarks that 100 per cent efficiency can hardly ever be attained, but he succeeded in attaining 10 per cent. This great discrepancy between theory and experiment may be due to the fact that the dynamical sensitivity (s) of the photo-electric element has a different value in the mosaic system from that in the conventional systems. The ratio between the output from the iconoscope and that from the scanning disc is

$$\eta = \frac{s_1 C_2}{s_2 C_1} n$$

where s_1 is the dynamical sensitivity of the photo-electric element of the scanning-disc system and s_2 that of the mosaic system, and n is the number of picture elements. That the static sensitivities of the systems are not equal has already been proved by the equation of F. Schröter and W. Ilberg*

$$I = \frac{aE}{b - E} L$$

where L is the illumination, E the anode voltage, I the corresponding current, and a and b the individual constants of the photo-cell. It seems evident, in view of the construction of the systems mentioned, that s_1/s_2 and also C_2/C_1 are each less than unity. Therefore η must be smaller than n, which seems to agree with the experiments.

Major R. Chalmers Black (*communicated*): The paper shows very clearly how essential it is to reduce inertia to a minimum if tolerably well-defined pictures are required. The synchronism between the sending and the receiving apparatus appears to be absolute, and apparently there need be little or no visible distortion of the received image. If, as appears possible, the apparatus can be relied upon to reproduce an image

* Paper by Dr. V. K. Zworykin (see vol. 73, p. 437).

* *Physikalische Zeitschrift*, vol. 30, p. 803.

precisely, there would seem to be a large field of application apart from the reproduction of entertainment programmes, which, so far, seem to have absorbed the greater part of the energies of television invéntors. The most obvious of these other applications is to supervisory apparatus for large distribution systems, or to enable those in control of any widely extended activity to obtain at any instant an accurate précis of the state of affairs at any point on the system. Instruments, meters, circuit breakers, and the like, could be so grouped as to be "seen" at will at the control point. A rather special application of this kind would be to "position finders" as used for range-finding, where two observers situated some distance apart take simultaneous readings on a target, a difficulty being to ensure that both observers view precisely the same part of the same object. Television apparatus of quite a simple nature would enable a check to be kept by comparing a direct view from one end of the base with the view televised from the other end. Though developed for use with radio channels, there would appear to be cases where television over wired channels would be advantageous, as, for example, repeating a stage play to a large audience within a small area, where it would seem quite feasible to use a multi-core cable giving 500 to 1 000 channels, each scanning one single line only. As the scanning speed would be quite low—20 to 25 lines per sec.—mechanically-controlled mirrors might be used; a bank of mirrors rotating continuously in one direction at some sub-multiple of 25 revs. per sec. Some such arrangement would permit of the use of a large screen and ample illumination. As the author points out, iconoscope and kinescope form an inertialess commutating or switching device capable of operating at really high speeds and apparently applicable to many problems in switching other than picture-scanning. One such application which suggests itself is to automatic telephone line-selecting, the iconoscope acting as a dialling switch at the subscriber's instrument, whilst the kinescope would function as the operator at the exchange. With some such arrangement it would seem possible to deal with up to, say, 10 000 lines. The calling subscriber would set up the desired number on a bank of cyclometer dials, which would so act on the optical system as to cause the scanning beam to come to rest on the mosaic at a point corresponding to the number called—there would be, say, 100 "levels" of 100 subscribers' numbers, corresponding to "jacks" on a manual switchboard. The kinescope at the exchange moving in synchronism with the iconoscope would show on its screen a spot of light which, passing through a negative lens—to spread out the area covered—would fall on a photoelectric cell of which there would be one per subscriber. The resulting current suitably amplified would operate a relay switching in the called subscriber. The amount of delicate apparatus involved would appear rather formidable and the difficulties to be met rather overwhelming, but the above are, I think, the lines along which future development may conceivably take place. The actual dialling time would be very small, as the whole of the "jacks" could be traversed in a fraction of a second. No attempt appears to have been made to make the apparatus suitable for giving images in natural colour. Television in colours seems to be beset with very real difficulties. Each colour band—three would seem to be a minimum—would seem to need a complete set of television equipment, including a separate communication channel unless the colours are transmitted in rotation, which would greatly complicate the synchronizing arrangements and would reduce to about one-third the number of picture elements, as each colour would require to be transmitted to each picture element separately. Colour, in effect, introduces a fourth dimension, necessitating a large increase of picture elements per sec. for faithful rendering of colour. The fluorescent screen does not lend itself to colour work. The particular substance used by the author, being sensitive to a narrow band in the green region of the visible spectrum, is quite unsuitable for any other colour. There are possibly other substances giving red or blue light when excited by the cathode ray, but all are probably far less sensitive than the substance used. In any case very drastic optical filtering would be necessary in order to obtain a correct colour balance. The evidence seems to show that the fluorescent screen, whilst excellent for quite small pictures in monochrome, is quite inadequate to deal with full colour or to give the size of picture necessary for public exhibition, these requirements apparently calling for entirely different methods.

Dr. V. K. Zworykin (*in reply*): As Dr. Babits suggests, the low efficiency of the iconoscope is undoubtedly due to the low effective photo-sensitivity of the mosaic. Our experiments indicate that while C_2/C_1 is approximately unity in the present type of iconoscope, the photo-sensitive ratio (s_1/s_2) is of the order of 1/10. This low ratio is not inherent in the photo-sensitive mosaic, and an investigation of the cause of the inefficiency, which, it is hoped, will lead to a remedy, is being carried on at present.

The comments of Major Chalmers Black on the numerous applications of the cathode-ray television system give a good idea of its future usefulness. At present the efforts of the Television Section of our Electronic Research Laboratory are devoted almost entirely to improving the method, but we hope that in the near future it will have reached a sufficiently high state of perfection to allow us to devote time to its many applications such as those described by Major Chalmers Black.

INSTITUTION NOTES.

Faraday Medal.

At the Ordinary Meeting of the Institution held on the 1st February the President announced that the Council had that day made the twelfth award of the Faraday Medal to Sir Frank E. Smith, K.C.B., C.B.E., D.Sc., F.R.S.

Honorary Member.

At the same meeting the President also announced that the Council had elected Dr. R. Thury, of Geneva, to be an Honorary Member of the Institution.

Members from Overseas.

The Secretary will be obliged if members coming home from overseas will inform him of their addresses in this country, even if they do not desire a change of address recorded in the Institution register.

The object of this request is to enable the Secretary to advise such members of the various meetings, etc., of the Institution and its Local Centres, and, when occasion arises, to put them into touch with other members.

Communications from Overseas Members.

Overseas members are especially invited to submit, for publication in the *Journal*, written communications on papers read before the Institution or published in the *Journal* without being read. The contributor's country of residence will be indicated in the *Journal*. In this connection a number of advance copies of all papers read before the Institution are sent to each Local Hon. Secretary abroad to enable him to supply copies to members likely to be in a position to submit communications.

Scholarships.

The Secretary desires to draw the attention of members to the following Institution Scholarships:—

Duddell Scholarship (value £150 per annum for 3 years). Open to British subjects under 19 years of age on the 1st July who have passed a matriculation or equivalent examination, and who desire to take up a whole-time day course in electrical engineering.

Ferranti Scholarship (value £250 per annum for 2 years). For whole-time research or post-graduate work. Open to British subjects under 26 years of age on the 1st July, who have been Students or Graduates of the Institution for at least 2 years and have taken either (*a*) a whole-time course in electrical engineering of at least 3 years and obtained a degree or diploma; or (*b*) a whole-time course in science of at least 3 years and obtained an honours degree, provided that in the final examination for such degree they have passed in "Physics," or "Electro-Chemistry," or "Electro-Metallurgy."

Swan Memorial Scholarship (value £120 for 1 year). The conditions are similar to those for the Ferranti Scholarship, except that the age limit is 27 years on the 1st July and that candidates need not be members of the Institution. Preference will be given to candidates who were born in the County Borough of Sunderland, or resided there for at least 7 years, or were educated at Sunderland Technical College.

Silvanus Thompson Scholarship (value £100 per annum, plus tuition fees, for 2 years). Open to British subjects who have served a minimum apprenticeship (or its equivalent) of 3 years at an approved works and are under 22 years of age on the 1st July, and who desire to take up a whole-time day course in electrical engineering.

The closing date for receiving nominations for this year's awards is the 15th April. Any member desirous of obtaining more detailed information should apply to the Secretary.

Graduateship Examination Results: November, 1933.

SUPPLEMENTARY LIST.*

Passed.†

Aldrich, L. R. (New Zealand).
Apte, R. Y. (India).
Avadhani, C. S. (India).
Cherry, D. M. (New Zealand).
Cleur, C. W. (India).
Davies, D. P. (Burma).
De, L. (India).
Dwyer, K. McI. (South Africa).
Joshi, M. S. (India).
Kelly, T. E. (New Zealand).
Lautier, V. (Malta).
Lehmann, W. W. (South Africa).
McLeod, P. H. (F.M.S.).
Manton, W. J. W. (China).
Miller, W. L. E. (China).
Modi, J. T. (India).
Nag, D. C. (India).
Nayak, U. P. (India).
Pomeroy, R. G. (South Africa).
Pritchard, J. N. H. (South Africa).
Ramachandra, G. S. (India).
Rao, S. R. (India).
Richards, C. G. (Straits Settlements).
Sahiar, J. H. (India).
Sink, H. (South Africa).
Sinnadurai, S. (Ceylon).
Squires, N. LeC. (New Zealand).
Stevenson, I. D. (New Zealand).

Passed Part I only.

Ainger, H. (New Zealand).
Allerston, P. (Egypt).
Anand, L. S. (India).
Banerji, S. K. (India).
Bharucha, B. D. (India).
Blacklaws, A. B. (South Africa).
Chari, R. S. (India).
Chellam, S. V. (India).
Disanayaka, S. C. (Ceylon).
Durrant, E. (India).
Ellawela, G. E. de S. (Ceylon).
Ennis, D. A. (New Zealand).
Fowlds, R. H. (South Africa).
Ghose, S. C. (India).
Hillary, H. W. (South Africa).
Janvekar, S. G. (India).
Khan, M. I. (India).
Laing, G. G. (South Africa).
Lewis, K. (South Africa).
Lilaoowala, K. N. H. (India).
MacHutchon, I. F. (South Africa).
McIndoe, J. K. (New Zealand).

* See page 199.

† This list also includes candidates who are exempt from, or who have previously passed, a part of the Examination and have now passed in the remaining subjects.

Passed Part I only—continued

Middha, S. C. (India).
Mohindra, L. C. (India).
Nagra, A. S. (India).
Nield, C. F. (Egypt).
O'Sullivan, R. A. (New Zealand).
Pattison, J. C. (South Africa).
Rajagopalan, K. R. (India).
Redpath, F. R. (New Zealand).
Sargeant, P. A. (South Africa).
Saroup, M. C. (India).
Sharma, R. K. (India).
Sohoni, K. V. (India).
Swann, S. B. (South Africa).
Theagarajah, M. (Ceylon).
Tillekeratne, T. S. V. (Ceylon).
Vajifdar, P. K. (India).

Passed Part II only.

Anderson, M. H. (New Zealand).
Banks, A. (South Africa).
Chari, S. K. (India).
Murty, K. R. K. (India).
Srinivasan, P. N. (India).
Tudhope, G. W. (South Africa).
Wheeler, A. G. (India).

Proceedings of the Wireless Section.

108th Meeting of the Wireless Section, 1st November, 1933.

Mr. P. V. Hunter, C.B.E., President, took the chair at 6 p.m.

The minutes of the meeting held on the 3rd May, 1933, were taken as read and were confirmed and signed.

A vote of thanks to Mr. L. B. Turner, M.A., for his services as Chairman of the Section during the session 1932–33, proposed by Col. A. S. Angwin, D.S.O., M.C., B.Sc.(Eng.)., and seconded by Mr. W. J. Picken, was carried with acclamation.

Mr. G. Shearing, O.B.E., B.Sc., Chairman of the Section, then delivered his Inaugural Address (see page 11).

A vote of thanks to Mr. Shearing for his Address was proposed by the President and, after being put to the meeting, was carried with acclamation.

The meeting terminated at 7.30 p.m.

109th Meeting of the Wireless Section, 22nd November, 1933.

Mr. G. Shearing, O.B.E., B.Sc., Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting held on the 1st November, 1933, were taken as read, and were confirmed and signed.

A discussion, which was opened by Mr. A. Morris, Member, took place on the subject of "The Interference of Electrical Plant with the Reception of Radio Broadcasting" (see page 245).

The meeting terminated at 8.0 p.m. with a vote of thanks, moved by the Chairman, to Mr. Morris and the other speakers.

110th Meeting of the Wireless Section, 6th December, 1933.

Mr. G. Shearing, O.B.E., B.Sc., Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting held on the 22nd November, 1933, were taken as read and were confirmed and signed.

A paper by Messrs. E. B. Moullin, M.A., Associate Member, and H. D. M. Ellis, B.A., Graduate, entitled "The Spontaneous Background Noise in Amplifiers due to Thermal Agitation and Shot Effects," was read and discussed.

The meeting terminated at 8.0 p.m. with a vote of thanks to the authors, which was moved by the Chairman and carried with acclamation.

111th Meeting of the Wireless Section, 3rd January, 1934.

Mr. G. Shearing, O.B.E., B.Sc., Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting of the 6th December, 1933, were taken as read and were confirmed and signed.

A paper by Mr. T. Walmsley, B.Sc., entitled "An Investigation into the Factors Controlling the Economic Design of Beam Arrays," was read and discussed.

The meeting terminated at 7.35 p.m. with a vote of thanks to the author, which was moved by the Chairman and carried with acclamation.

112th Meeting of the Wireless Section, 7th February, 1934.

Mr. G. Shearing, O.B.E., B.Sc., Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting held on the 3rd January, 1934, were taken as read and were confirmed and signed.

A paper by Messrs. L. H. Bedford, M.A., and O. S. Puckle, Associate Member, entitled "A Velocity-Modulation Television System," was read and discussed.

The meeting terminated at 8.15 p.m. with a vote of thanks to the authors, which was moved by the Chairman and carried with acclamation.

Proceedings of the Meter and Instrument Section.

39th Meeting of the Meter and Instrument Section, 3rd November, 1933.

Mr. P. V. Hunter, C.B.E., President, took the chair at 7 p.m.

The minutes of the meeting held on the 5th May, 1933, were taken as read and were confirmed and signed.

A vote of thanks to Mr. R. S. J. Spilsbury, B.Sc.(Eng.), for his services as Chairman during the session 1932–33, proposed by Mr. G. A. Cheetham and seconded by Mr. Wilfred Holmes, was carried with acclamation.

The President then vacated the chair, which was taken by Mr. W. Lawson, Chairman of the Section, who delivered his Inaugural Address.

A vote of thanks to Mr. Lawson for his Address, proposed by the President and seconded by Mr. F. E. J. Ockenden, was carried with acclamation.

The meeting terminated at 8.15 p.m.

40th Meeting of the Meter and Instrument Section, 1st December, 1933.

Mr. W. Lawson, Chairman of the Section, took the chair at 7 p.m.

The minutes of the meeting held on the 3rd November, 1933, were taken as read and were confirmed and signed.

Papers by Dr. A. H. M. Arnold, Associate Member, entitled "Leakage Phenomena in Ring-Type Current

Transformers" and "Current-Transformer Testing" respectively, were read and discussed.

The meeting terminated at 9.20 p.m. with a vote of thanks to the author, which was moved by the Chairman and carried with acclamation.

41st Meeting of the Meter and Instrument Section, 5th January, 1934.

Mr. W. Lawson, Chairman of the Section, took the chair at 7 p.m.

The minutes of the meeting held on the 1st December, 1933, were taken as read and were confirmed and signed.

A paper by Mr. J. B. Lees, Associate Member, entitled "The Equipment of a Modern Meter and Test Department," was read and discussed.

The meeting terminated at 9.30 p.m. with a vote of thanks to the author, which was moved by the Chairman and carried with acclamation.

42nd Meeting of the Meter and Instrument Section, 2nd February, 1934.

Mr. R. S. J. Spilsbury, B.Sc.(Eng.), took the chair at 7 p.m., in the absence of the Chairman.

The minutes of the meeting held on the 5th January, 1934, were taken as read and were confirmed and signed.

A paper by Mr. J. Henderson, M.C., B.Sc., Associate Member, entitled "Grid Metering," was read and discussed.

The meeting terminated at 10 p.m. with a vote of thanks to the author, which was moved by Mr. Spilsbury and carried with acclamation.

Elections and Transfers.

At the Ordinary Meeting of the Institution held on the 18th January, 1934, the following elections and transfers were effected:—

Elections.

Associate Members.

Barbour, Frederick Lumsden.
Beighton, Thomas Arthur.
Beruldsen, Joseph Bertrand.
Best, Kenneth Barrington.
Brent, William Henry, B.Sc.
Butt, Sidney Frank.
Byrne, Patrick, B.E., B.Sc.
Campbell, Duncan, B.Sc. (Eng.).
Cawsey, Alfred John.
Chittenden, John Picton.
Cobbold, Rowland Hope, B.A.
Davies, Frederick Leighton
Davis, Neville Ryland, M.A.
Downie, Christopher Gordon, B.Sc.
Elliot, John.
Emery, Edward, B.Sc. (Eng.).
Graham, Douglas Harry, B.Sc.(Eng.).
Gray, Albert Hilliard.
Hall, Albert.
Hartwell, Leonard William, B.Sc.
Hazell, James Temple.
Hetherington, Thomas.
Hibberd, William Alfred.
Hill, Cyril Charles, B.Sc. (Eng.).
Hounsell, Harold Reginald.
Kellie, John Gordon, M.Eng.
King, Charles.
Knight, Edwin William.
Lackie, David Lamond, B.Sc.
Mackenzie, William Grant, B.Sc.
Main, Arthur Charles, B.E.
Mead, Ernest, B.Sc.(Eng.).
Miles, Percy Vincent C. R.
Morris, Arthur John.

Associate Members—continued.

Neale, Roland Hayward R., Major.
Nichols, Oretie Stanley.
O'Meara, Alfred, B.Sc. (Eng.).
Overholm, Hakan.
Pannett, William Edward.
Poole, John Copeland.
Preston, John Silvey, M.A.
Rand, Clifford Percival N., M.A.
Richards, Edward Arthur, B.Sc.(Eng.).
Rowlands, Thomas William, B.Sc.
Semple, Leslie George, B.Sc.
Sutton, Charles Thomas W., B.Sc.(Eng.).
Tugwood, John Richard, B.Sc.
Turner, Claud William C., Lieut.-Commdr., R.N.
Witts, Albert Charles G., B.Sc.

Companion.

McGill, William.

Associates.

Bent, Reginald Harvie.
Bowler, William Charles.
Brown, Duncan Eustace T.
Coventry, Arthur Frederick.
Coward, Hervey James V.
Cowlishaw, Frank.
Gardner, James Neilson.
Garside, Frederick.
Gilbert, Neville Wallace.
Glover, Cyril Albert.
Griffin, Aidan.
Horabin, Willis.
Johnson, William Edgar.
Jones, Percy Lewis.
McKay, Hugh Stewart.
Milne, Alexander.
Mistry, Rustomji Dossabhoy.
Morgan, Rowland Henry.
Pym, John Frederick.
Reed, Herbert John.
Royce, Howard Mark W.
Smith, John Johnson.
Thuraiappah, Poothathamby Sinnacutty.
Todd, Albert Henry.
Whalley, David Ellicott.
Winstanley, Samuel.

Graduates.

Airey, Arthur Charles.
Alexander, George Wellington, B.Sc.
Alexander, Robert Fyfe.
Armitage, Herbert.
Athalye, Dattatray Ganesh, B.A., B.Sc.
Atkins, Cyril James.
Aubrey, Richard.
Bell, David Arthur, B.A.
Bentley, Roland David, B.A.
Bhagat, Bhagwandas Pessumal, B.Sc.
Blackie, James.
Blears, Jack.
Boddam-Whetham, Alexander David.
Browning, Jeffery Bellingham.
Burrows, Thomas Kenneth.
Carter, William Hutton, B.Sc.
Chatterji, Sontosh Kumar, B.Sc.
Connelly, Dennis, B.Sc.
Connelly, Frank Cecil, B.Sc.
Cook, Eric Howard.
Crean, Joseph Raphael, B.Sc.(Eng.).
Cross, Edwin Arthur.
Cureton, Alan Robson.
Dinsmore, Harry.
Dowling, Alfred Jeffery.
Drummond, Bernard Gilbert, jun.
Eyre, Charles Malton LeG.
Fletcher, Paul Thomas, B.Sc.(Eng.).
Fortescue, Richard Lewis, B.A.
Gauntlett, John Richard, B.Sc.
Gay, Harold.
Gelder, William Alfred E., B.Sc.
Ghose, Tejesh Chandra, B.Sc.
Gibson, Henry William.
Goodman, Emile William, B.A.
Greenwood, Herbert.
Hack, Jack.
Harding, George Nelson.

Graduates—continued.

Harry, Donald Maltby.
Hart, John Cecil.
Hind, Harry.
Hobbins, Henry.
Holden, Eric Kenyon, B.E.
Holroyd, Clement, B.Sc. (Eng.).
Ivinson, John Reginald.
Jackson, Frederick, B.Sc., B.E.
Jones, Archibald Llanwyn, B.Sc.
Jones, George Frederick.
Jones, William David, B.Sc.
Koh, Nye Poh, B.Sc.
Laflin, Harry Ernest.
Lane, Henry Otto.
Lee, Walter Herbert.
Mackintosh, Ian William.
Maisey, Harold Roberts.
Malhotra, Lakshmi Chand.
Mansukhani, Atmaram Teckchand, B.Sc.(Eng.).
Marathe, Dattatray Hari.
Marillier, Arthur Frederic R., B.Sc.(Eng.).
Marr, Norman Carse, B.Sc.
Marsh, Frank.
Marsh, Thomas Francis H.
Mehta, Kalidas Himatlal, B.Sc.
Millman, Charles Henry.
Montgomery, Stuart Haldane.
Moulton, Harrison Ralph, B.A.
Newborough, Robert.
Norman, Edgar James, B.Sc.(Eng.).
Oliver, George Francis N., B.A.
Park, John Grimes.
Perkins, Leslie Brigg, B.Sc.
Price, Ronald Hartley.
Price, Wesley Owen.
Rasiah, Victor Jayaratnam.
Ravno, Albert, B.Sc.(Eng.).
Reveley, Paul Vernon, B.Sc.
Roberts, Wilfrid Emlyn.
Robson, Harold.
Rogers, Christopher John.
Scott, Sydney Wallace.
Simon, Alexander, B.Sc.
Smith, John Allen.
Sofair, Selim Ishaq, B.Sc.
Stevens, James Ambrose, B.Sc.
Suttie, Thomas Frederick, B.Sc.(Eng.).
Tarrant, Frederick George.
Thorne-Pool, Norman Hector.
Vashkoff, Nicholas.
Voaden, Richard Philip B., B.Sc.
Walker, Alexander William P.
Wallace, George Alister, B.Sc.(Eng.).
Werrell, John Valentine, B.Sc.(Eng.).
Williams, Richard George.
Worsley, Francis Arthur, B.A.
Wright, Hilary George H.
Wyman, Hubert Lionel D.
Yeates, Gordon Ashley, B.Sc.(Eng.).

Students.

Abbott, Frederick Donald.
Abd-el-Kader, Hussein Hassan.
Abel, Harry Lewis.
Aird, Robert Harker.
Alizia, Mian Yusuf.
Allan, Alexander William.
Allen, Jack.
Almond, George.
Anand, Labh Singh.
Antram, Arthur Burnaby.
Ashford, William John A.
Ashton, Geoffrey Alec.
Atkinson, Richard Ashley.
Austin, John T.
Avadhami, C. S.
Ball, Albert Herbert.
Barber, Howard John, B.Sc.
Barber, Thomas George.
Barugh, Jasper Kendall.
Batty, Frank Sudbury.
Beauchamp, Kenneth George.
Bertram, John.
Bhullar, Gurdit Singh.
Bilbrough, Richard Brooks.
Binks, George James.
Black, Robert Frankston.
Blakeley, Philip William.
Blascheck, Alexander Charles.
Blench, Ralph Edwin.
Blomeley, Garside Yeadon.
Bloxsidge, William Robert.
Boston, David Whitehead.
Bowles, Arthur Horace W.

Students—continued.

Bradley, John Harvard.
Breeze, Eustace Henry N.
Briars, Ernest.
Brighton, Allan Norman.
Brooks, Norman Colston.
Brown, Allan Harry.
Browne, Maurice Hubert W.
Bruce, James Robert.
Bruty, Alfred Owen.
Buchanan, Ian Philip J.
Buckley, George Vernon.
Butail, Roshan Lall.
Buttner, Albert.
Byram, Harold.
Bywaters, Gilbert Ivor A.
Cahill, James Patrick.
Carrette, Alan Desmond.
Chaplin, Gilbert.
Chapman, Frederick Faulkner.
Char, D. B. K.
Chatterton, Rex John B.
Cheek, Tom.
Cherry, Donald Manwaring, B.Sc.
Child, Cecil.
Chilton, Leslie.
Clapham, John Anvan.
Clarke, Alan Charles W. V.
Clarke, Roi Logan.
Clegg, Jack Leslie.
Clegg, John Ernest.
Clutton, Rex Gordon H.
Codd, Ernest Edward A.
Cole, Sydney Herbert.
Collins, John.
Connor, George Rochfort.
Constance, Ernest Raymond.
Cooper, Charles Peter.
Cope, Francis Bernard.
Copinger, Walter Patrick.
Coupe, Kenneth Wilson.
Cranfield, Ernest.
Curtis, Arthur Gardiner.
Darby, William Ernest.
Darwin, John Francis.
Darwon, William Thomas.
Das, Sauresh Chandra.
Davies, Edward James L.
Davies, John Morley.
Davies, William.
Davy, Norman Thomas J.
Dawson, Maurice Woodhouse.
D'Costa, Arthur Joachim E.
Deshmukh, Bhagwant Vyanktesh, B.Sc.
Dey, Douglas George.
Disanayaka, Sydney Clarence
Donovan, Grahame Walter.
Dummer, Norman.
Dungey, Alan Cecil.
Dunkley, Geoffrey Harington.
Durnford, John.
Durrant, Edward.
Dutt, Probhat Chunder.
Easterbrook, John Lewis.
Ellawela, George Edward De S.
Euler, Henry Leonard.
Everett, Norman Clifford.
Exley, James.
Farnhill, Edward Seymour.
Fennessy, Edward.
Ferry, Thomas.
Fleming-Williams, Brian Clifford, B.Sc.
Fletcher, Benjamin.
Fletcher, Joseph Norman.
Foot, George Helier.
Freeborn, Kenneth Lionel C.
French, Ronald Richard.
Fyfe, Robert.
Gadsby, Harry Desmond S.
Gadsby, William John.
Gajapati Rao, Bondada, B.A.
Ganesh, Ramon Nathan.
Gaunt, Arthur Cambidge.
Gepfert, George Albert.
Ghalib, Selchouk Ahmed.
Gibas, Hubert Anton S.
Gibson, Albert James.
Gibson, John Francis A., B.Sc.
Gifford, Vernon Alexander J.
Gilmartin, William Craig.
Gleadle, George Musgrave.
Goodfriend, Isaac Theodore.
Gordon, Robert Connolly.
Greatrex, Ferdinand Basil.
Green, Frank Holding.
Green, John William.
Griffiths, Arthur Lewis.
Grisdale, George Lambert.
Hague, Arthur.
Hague, George Edward P.
Hakim, Syed Abdul.
Hall, Christopher Warren.
Hall, Eric.
Halliwell, George Gerald F.
Hammersley, Reginald Mark H.
Handyside, John Stewart.
Hare, Henry John.
Harper, William Eric.
Harris, Bernard John.

Students—continued.

Harris, Noel Meryon.
Harrison, Henry Mounsten.
Hatt, George William.
Haworth, Vernon.
Hazel, Arthur Curwen.
Hemingway, Joseph Wilson.
Henchley, Terence Richard B., B.Sc.(Eng.).
Henley, Donald Ernest G.
Hepworth, Sydney Leonard.
Hill, Harold.
Hill, John Norman.
Hogg, Francis Granville.
Holmes-Smith, Franklin.
Hope, Roy.
Hopgood, Stanley William.
Houghton, Bernard William.
Howie, Norman James.
Hunter, John Hardwicke C.
Hutchison, William Milne.
Ibbotson, Donald Briggs.
Illidge, Herbert Waller.
Ingleby, Joseph Holden.
Jackson, Walter Fielden.
Jagger, Albert Ernest
Jakeman, Frederick Ronald.
James, Leslie Francis.
Jan, Ahmad Sheikh.
Janvekar, Shankar Ganesh, B.Sc.
Jarvis, Harold Frederick.
Jay, Joseph Arthur.
Jenkins, William Bingham.
Jensen, Alan Richard C.
Johnson, Edmund Brandon.
Jones, Alan Fredrick.
Jones, David Evered H., B.Sc.
Jones, Edward, B.Sc.(Eng.).
Jones, Leslie Colston.
Jones, Reginald Hargreaves.
Kanwar, Dalip Singh.
Kemsley, John.
Kendall, John Laurence.
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Zainal, Raja.

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Whitcher, James.
Wilson, Francis Joseph H.

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Jones, Richard.
Metz, Louis Gerald E.
Pairman, Rodion.
Roberts, Frank Rob C.
Somayajulei, Bulusu Rama.

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Anderson, Charles.
Atkinson, Cyril Nicholas.
Bartley, William Coppen.
Beckingsale, Alfred Alec.
Bowker, Henry Charles, Ph.D., B.Sc.(Eng.).
Budgett, Felix La Tourette, B.Sc.(Eng.).
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Carnegie, James.
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Dempsey, John.
Duffield, Frederick Charles.
Dunn, John Frederick.
Faragher, Arthur John, B.Sc.Tech.
Fitzpatrick, Hugh James, B.Sc.
Ford, Wallace, B.Sc.
Fowler, Geoffrey, B.Sc.Tech.
Friedberg, Zvi, Dipl. Ing.
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Gould, Leslie Spencer, B.Sc.
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Harvey, David James.
Hickey, Matthew Gerard.
Hunter, John.
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Lonsdale, Robert.
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Warren, Sidney Harvey.
Welch, Jack Warwick F.
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Wilson, Peter Murray.
Wood, John Lind.

Student to Associate Member.

Bryl, Zygmunt, B.Sc.(Eng.)
Cash, Peter Watson, B.Sc.(Eng.).
Flowers, Thomas Harold, B.Sc.(Eng.).
Fuller, Arthur Leslie.
Hitt, Donald George, B.Sc.(Eng.).
Holmes, Malcolm Graham, B.Sc.(Eng.).
Knox, Arthur Horace, B.Sc.(Eng.).
Terry, Victor John, B.Sc.(Eng.).
Wilson, Roger Walter, B.Sc.(Eng.).

Student to Associate.

Adamson, Maurice William.
Barnes, Arthur.
Thynne, Arthur William.

The following transfers have also been effected by the Council:—

Student to Graduate.

Beatson, Cedric James, B.Sc.(Eng.).
Bowden, Charles.
Bowen, William Harold, B.Sc.
Burkitt, James Kent, B.Eng.
Cock, Charles Edward.
Cooper, Lionel Walter.
Cornfield, John Maxwell.

Student to Graduate—continued.

Creighton, James Leslie.
Cull, Robert Stephen.
Dummer, Geoffrey William A.
Flint, Ernest Alfred.
Floyd, William Frederic, B.Sc.
Foster, Eric Hugh.
Gray, John.
Harding, Robert Joseph.
Harman, Robert Charles.
Harrap, George Vaughan.
Henley, John Allan, B.Sc. (Eng.).
Jennett, William Joseph, B.Sc.(Eng.).
Johnson, Winton Thomas, B.Sc.
Jones, Harold Hosgood.
Koshairy, Mohammed Abdel B. El, B.Sc.
Lancaster, John Bretland, B.Sc.
Langford, William Lawton.
Lewis, Nicholas Noyes.
Low, Wilfred Charles, B.Sc.
Mackie, George William G.
Mansell, Frederick Raymond W. K., B.Sc. (Eng.)
Meek, Colin Alfred, M.Sc.

Student to Graduate—continued.

O'Kane, Bernard John, B.Eng.
Onslow, William George.
Parsons, William Richard, B.Sc.(Eng.).
Paulin, Kenneth Nelson.
Pillans, Gerald Scarth.
Prince, Harry Leslie.
Rawlinson, Robert.
Ridge, George Royston C.
Roy, Philip Scott.
Shaw, Clement William, B.Sc.(Eng.).
Silverman, David.
Sime, Thomas Livingstone, B.Sc.
Stephenson, Wilfrid Hector.
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Thomas, Evan James C.
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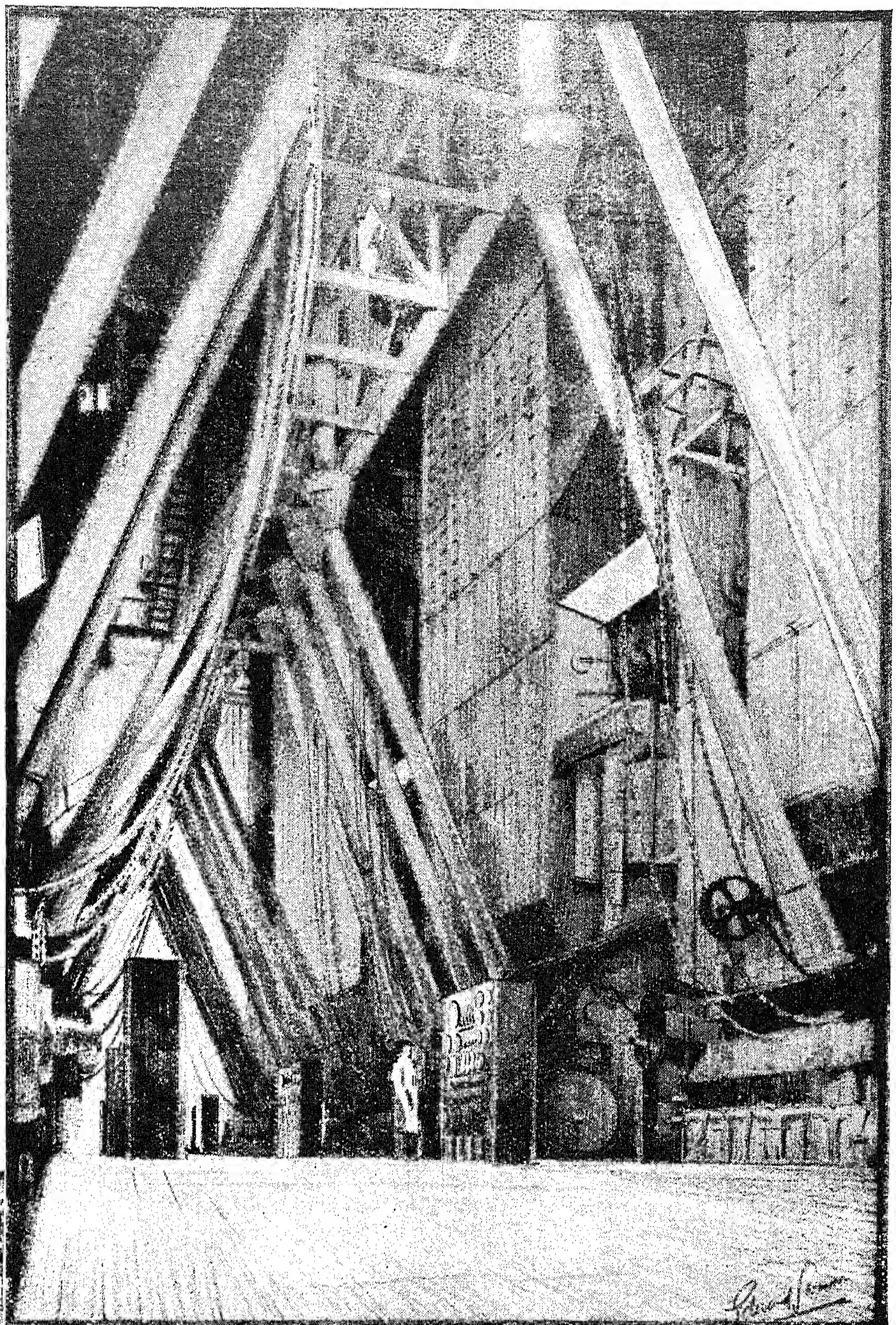

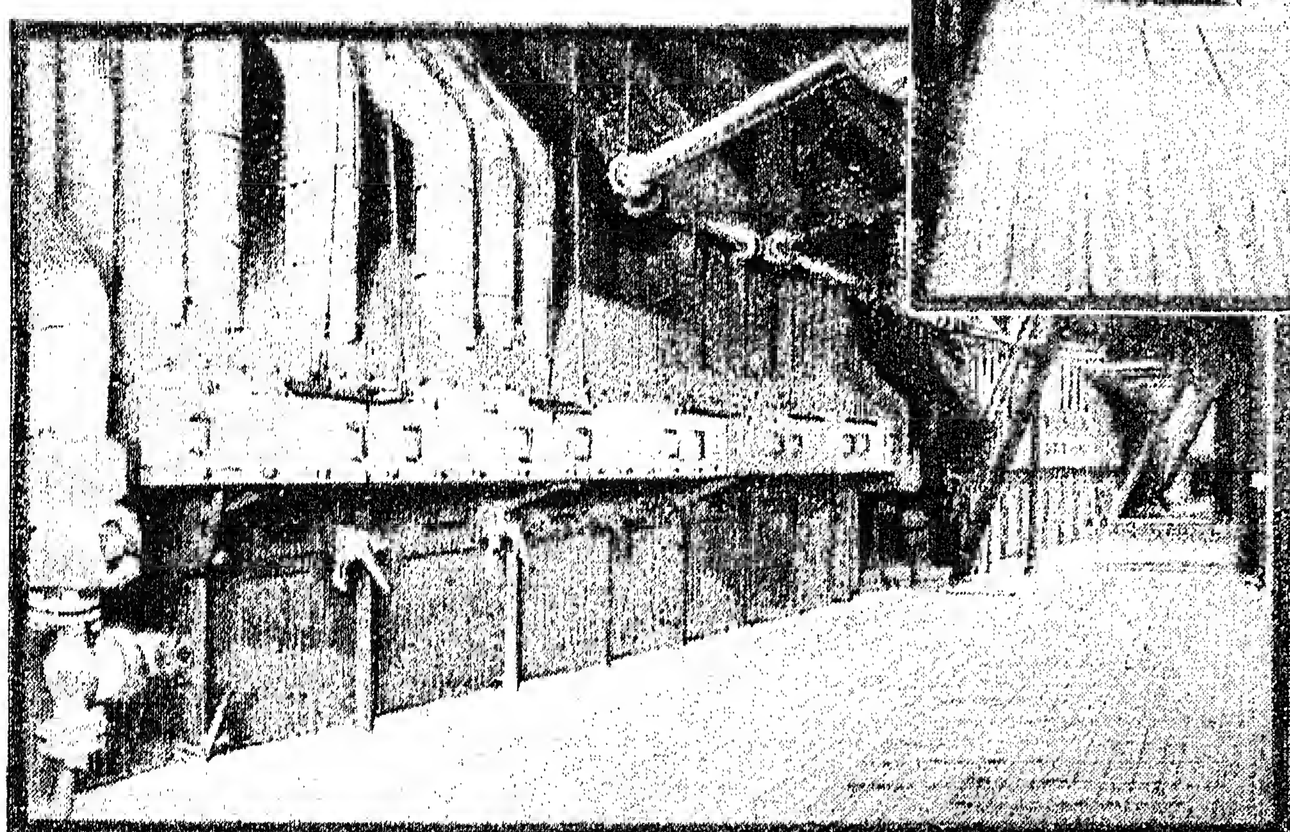

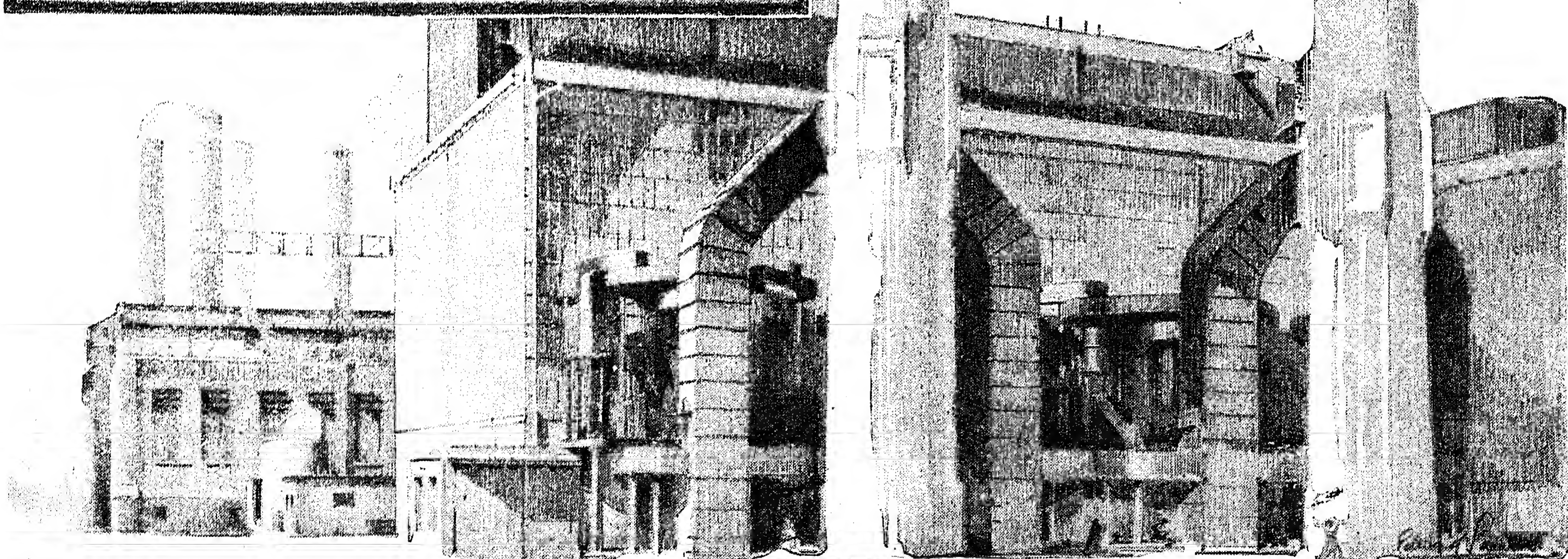

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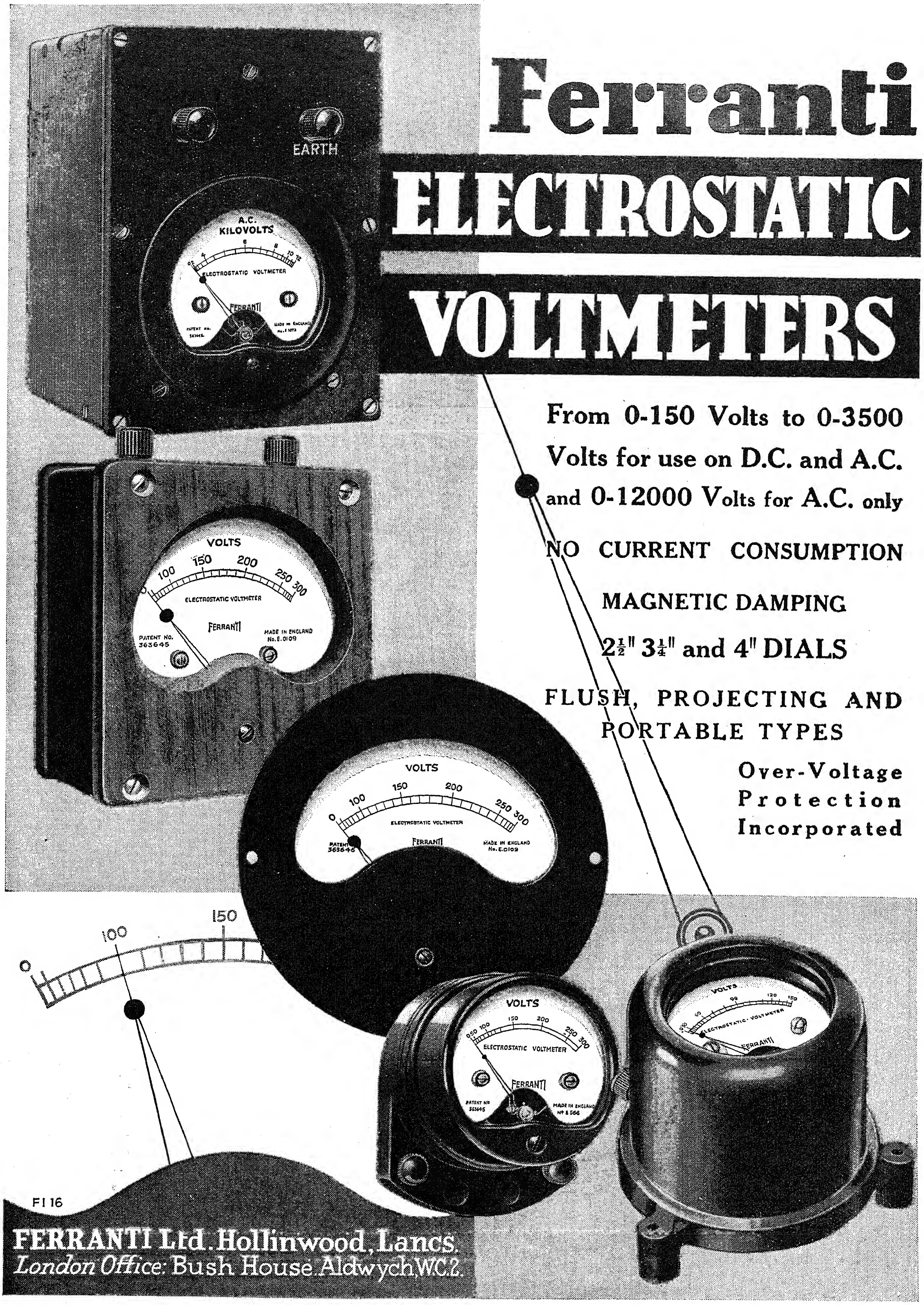
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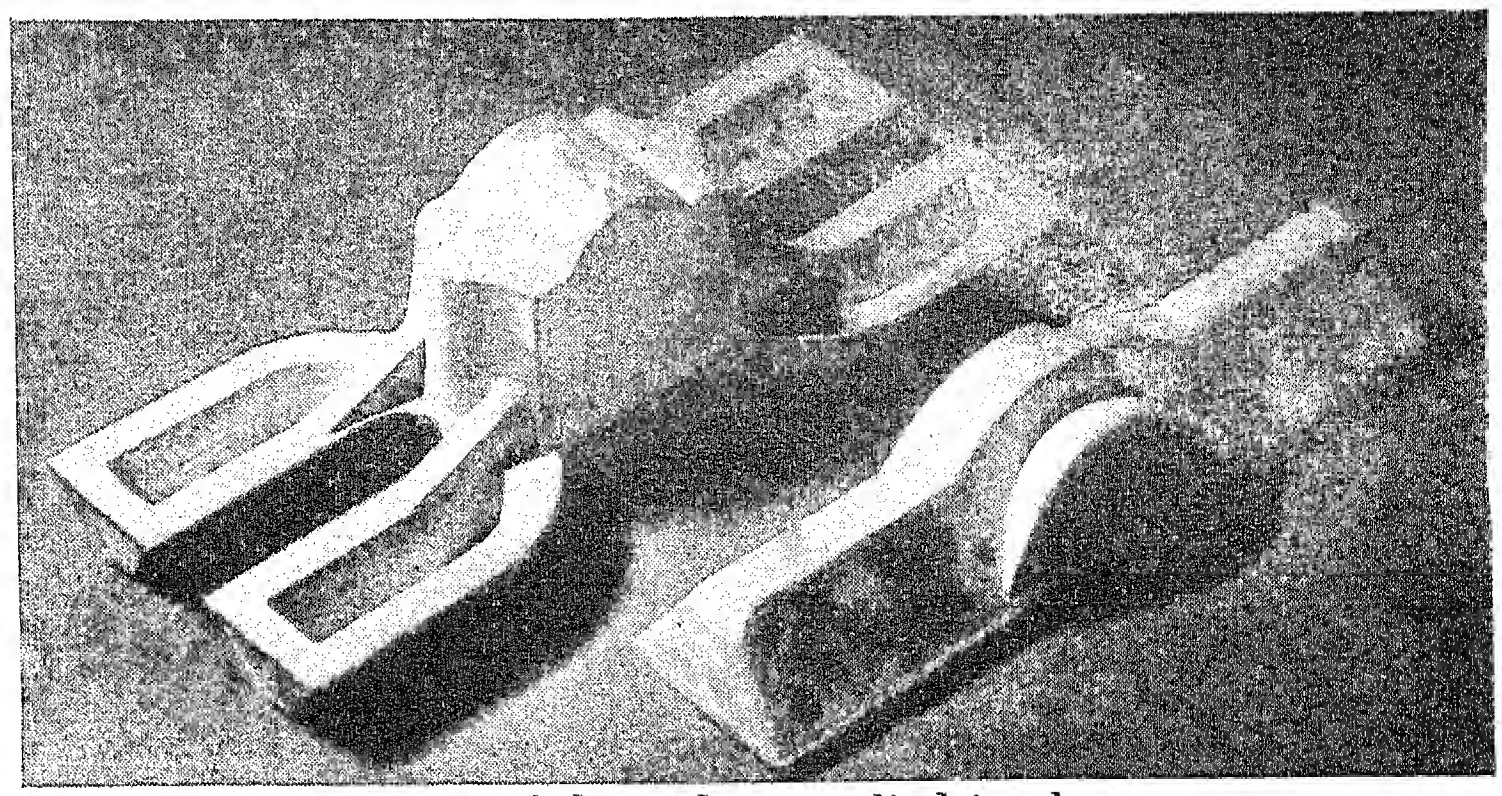

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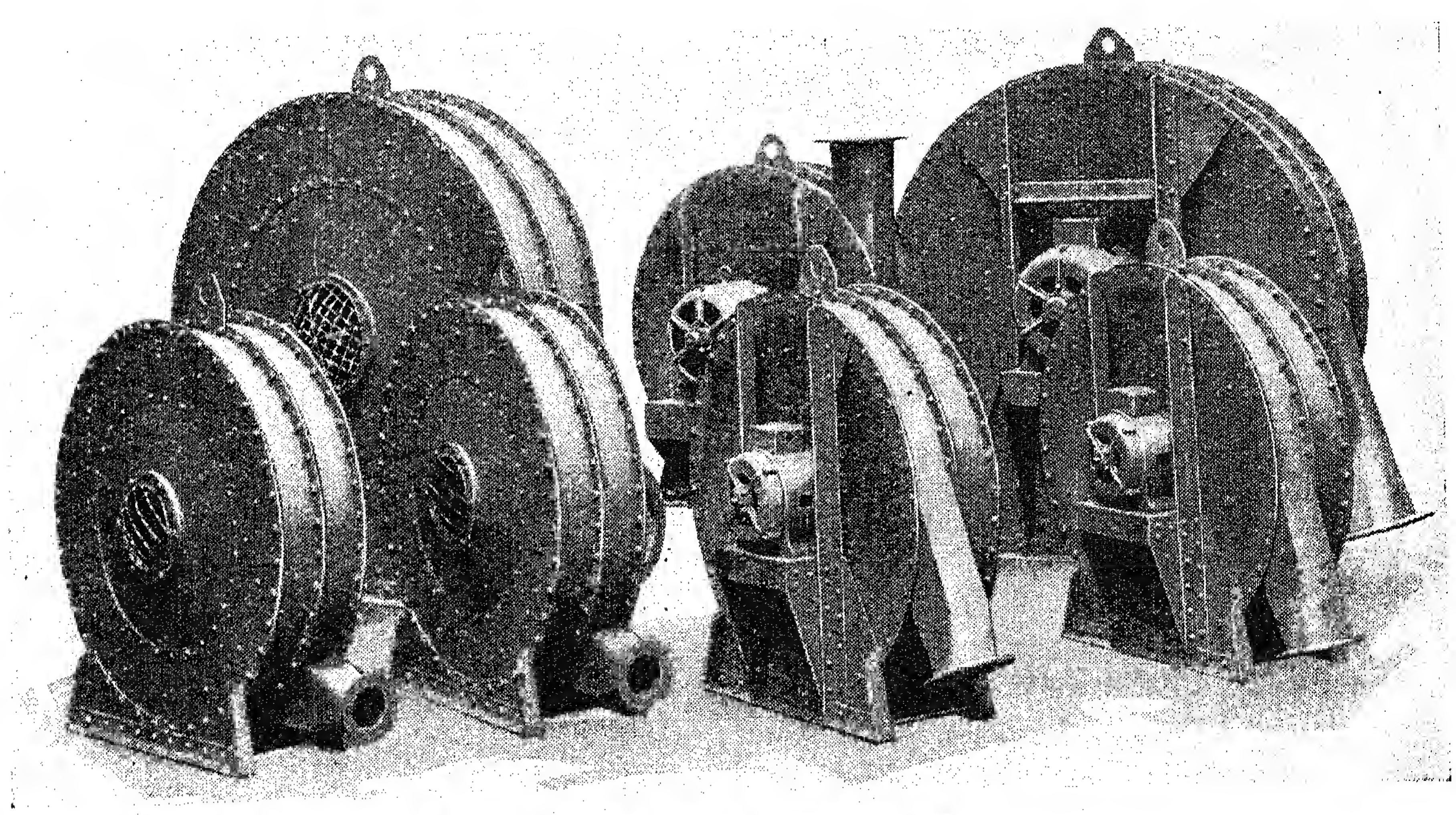

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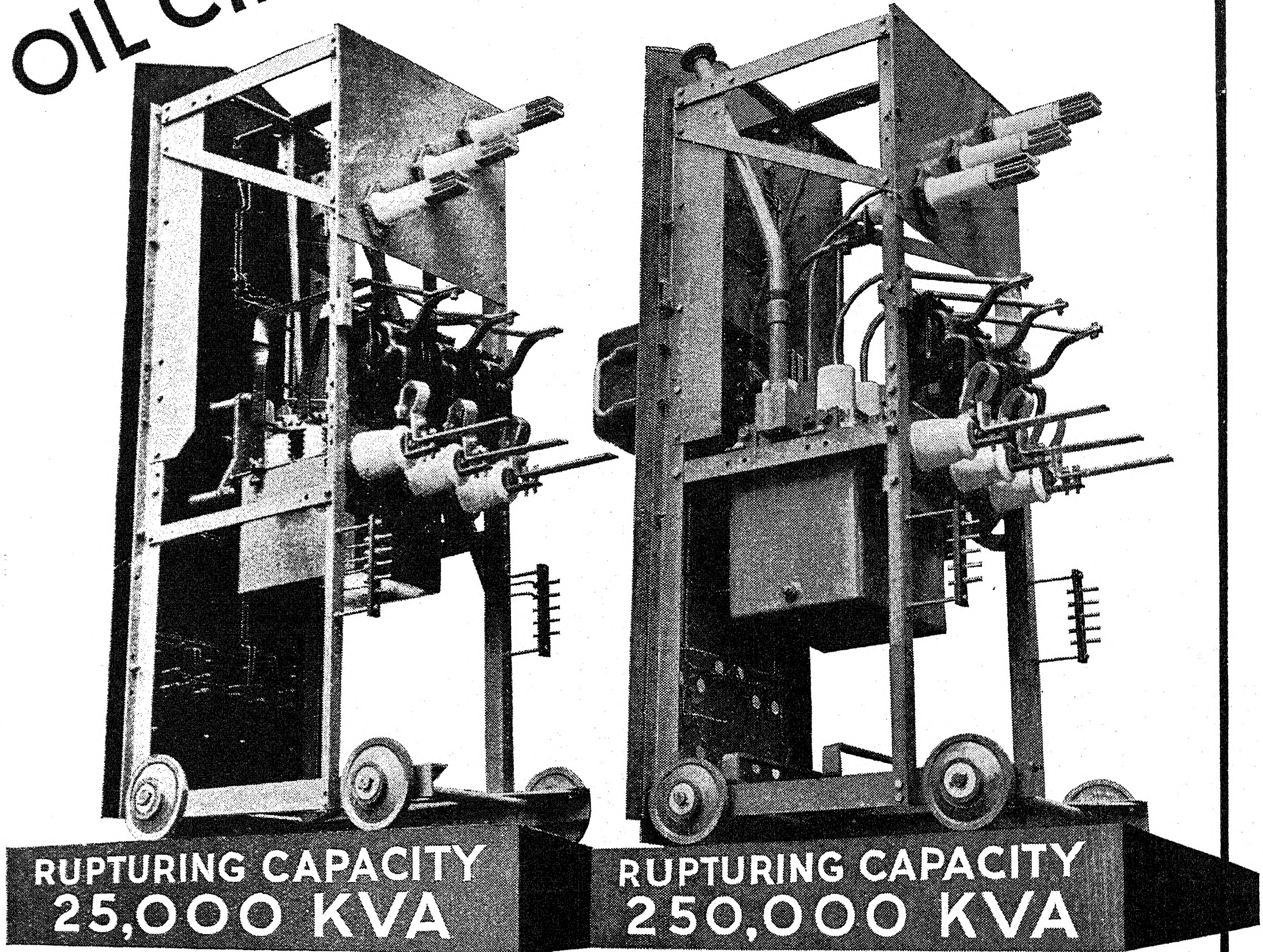

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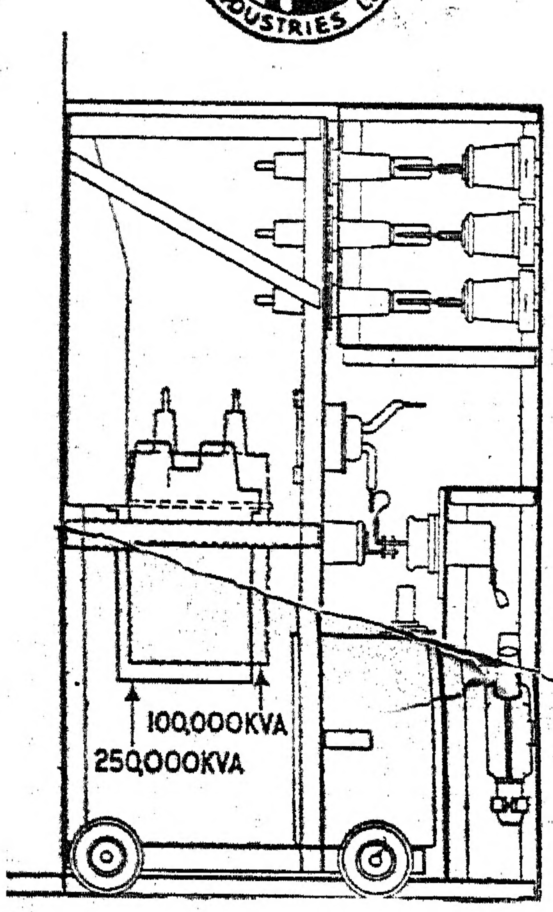

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